# WIND MACHINE INDUCED CHANGES IN THE NOCTURNAL MICROCLIMATE OF A CITRUS GROVE

By

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# INTRODUCTION

Florida, the largest citrus producer in the United States as well as in the entire world, had its industry drastically reduced by the 1962-63 freezes from 549,100 acres to 456,000 acres according to Schuler and Scarborough (76). This acreage produced 64 percent of the world's grapefruit and 23 percent of the world's oranges.

From the citrus fruits themselves and the by-products manufactured from them, the State of Florida derives over one-quarter of its agricultural income. Since the Florida economy is primarily based on agricultural income and tourism, the citrus industry plays a vital role in maintaining Florida's economy on an even keel.

Protection of horticultural crops, especially citrus fruits and trees, from freezing and frost is an important and serious problem to the Florida grower. Citrus growers for many years have sought methods of protecting their crops from the ravages of cold weather. Freezes are not new to the Florida peninsula and the citrus industry since notable freezes have occurred in 1886, 1894-95, 1899, 1917, 1928, 1934, 1940, 1957-58 and most recently in 1962-63 (57).

Frost and cold protection methods have been used in Florida since before the turn of the century. Early attempts to heat were not based on scientific research but

rather on observations of individual citrus growers. Probably the first method of grove heating was to burn native fat pine wood. Fat pine is the heart wood or resin-filled wood of native Florida pine and was readily available at low cost. Ultimately the supply of fat pine was depleted to the point where other fuel sources, such as coke, charcoal and various oils, were substituted. Some early observations on Florida heating can be found in articles by Camp (28), Phillips (66), Skinner (77), Stevens (78), Tilden (80), Varn (86) and Ward (89).

Wind machines have been in use in California since the early 1920's as a means of cold protection but failed to attract much attention in Florida until several decades later. Frisbe (38) wrote in March, 1952, that the only known installation of a wind machine in Florida was in the Lake Garfield Nurseries. Since this initial installation, the wind machine has become a common sight in Florida citrus groves. Georg (40) made early observations on wind machine performance in nurseries and groves. The earliest research at the University of Florida by Busby (26) was carried out in a peach orchard at the Horticultural Unit of the University northwest of Gainesville.

The Florida citrus grower has another aid available to him other than temperature modifying equipment. The Federal State Frost Warning Service, established in 1935, with operational headquarters at Lakeland, Florida, sends out grower forecasts each winter 3 times daily by radio, television and a teletype network.

Because of the increase in the wind machine population and recent damaging freezes, the Florida Agricultural Experiment Station, Department of Fruit Crops, at Gainesville, has been engaged in wind machine research in citrus since 1961.

Research concerning cold protection and heat transfer with wind machines was deemed important and was initiated at Orange Lake, Florida, to seek additional information in the following areas: (1) to determine the extent wind machines can afford adequate protection to citrus from cold temperatures, (2) to develop satisfactory instrumentation for the study of nocturnal microclimate in a citrus grove, (3) to determine the basic nocturnal microclimate and to evaluate the nocturnal heat budget as it exists during the months of probable frost and freeze damage and (4) to possibly formulate a better method of making evaluations for wind machine placement and use.

## LITERATURE REVIEW

### Historical

Since the time of Pliny the Elder, 77 A.D. and in all probability prior to his era, farmers and other persons associated with horticultural crops have been seeking more and improved methods to protect plants from frost and cold temperatures (92). Pliny the Elder in his "Natural History" published in 77 A.D. advised the farmers of his day when they were threatened by the danger of frost to "make bonfires in the fields and vineyards of cuttings and heaps of chaff or else weeds that could be rooted up; the smoke will act as a good preservative."

While we have come a long way since that time, we have not ceased to seek a more satisfactory method for the protection of crops from frost and cold; one that will guarantee protection at all times. Florida citrus groves by far the greater portion of the time are safe from severe injury, but past experience has shown it would be unwise and in vain for the grower to assume he can rely on chance and nature for protection against severe damage when major freezes occur.

Literature dealing with frost and cold protection of citrus trees and fruit describes many methods and applications. Probably more work has been done on heating devices,

fuels and their application than any other form of frost or cold protection.

Irrigation for cold and frost protection has been tried but in many instances has failed. Early work in this area was described by Jones (60) using furrow irrigation. More recently sprinkler irrigation has been used for frost and cold protection as outlined by Dean (32), Harrison and Dowling (52) and Pogrell and Kidder (68). Other protection methods include smoke covers, vapor barriers, chemical foams, hormones, infrared devices and artificial covers of various types.

The earliest attempts to use air transporting machinery were made in Europe according to Kessler and Kaempfert (61). These machines were very small compared to the machines of today and were used in fields or vineyards. In 1914 in Germany, horizontally directed fans mounted 6 to 7 feet above the soil were used to test the theory of mixing air close to the ground. This and other tests of a similar nature were tried by European researchers, but seldom over a 2 to $5^{\circ}$ F rise could be noted and this over a very small area.

Based on the findings of Young (92), who in 1920 measured inversions to the height of 40 feet, several California citrus growers attempted to build air transporting machines. Baker (9) in 1922 described a "frost preventer" consisting of an 18-inch pipe projecting 30 to 40 feet above the ground surface. Air was pulled down the pipe by the fan located at

the base and then discharged into a network of casings laid on the surface of the ground. The casings had openings or ports between the trees which allowed the air from 40 feet to be mixed with that at the soil surface.

In 1924, Young (93) published photographs of 4 air-moving devices designed and built by various citrus growers in California. None of the 4 worked adequately over a very large area, failing to penetrate against the drift more than 50 feet from the point of initiation. The most effective was a pagoda-shaped building with a large horizontal propeller moving air down across the roof surface where it mixed with hot air from a furnace inside the building. This was one of the earliest attempts to combine heat with forced air movement by a fan.

By 1928, tower-mounted fans were in use in California (7). Fans were mounted on 25-foot towers at Santa Fe Springs, California, and appear to be the prototype of present day machines used in the United States. These machines rotated a full 360 degrees every 4 minutes and gave protection to approximately 2 to 3 acres.

Moses (64) estimated that there were 150 wind machines in use in California by 1938. The majority of these machines were constructed by individual growers or small machine shops and varied considerably in power and design. Johnston (59) reported 75 wind machines in Tulare County in 1939, 52 electric and 23 gasoline-powered models. He also stated that following the 1937 freezes many California

growers decided to supplement the wind machines with heaters to assure adequate protection.

During World War II, 1941 to 1945, little was published about the wind machine due to concentration of effort on the machinery of war. Brooks et al. (16) in California, Frith (35) and Shaw and Redlich (75) in Australia began to experiment with the wind machines again in 1948.

Following World War II, the manufactured wind machine models made their appearance, and individually built grower machines became less common. The mass produced machines were available at several different horsepower ratings in gasoline, diesel and electric models. The majority of these wind machines used standard airplane propellers with different blade lengths and pitches. Later machines used fans specifically engineered to produce maximum air mixing.

The first description of an operational wind machine in Florida was made in 1952 by Frisbe (38). Following this initial installation, the wind machine did not show a rapid increase in popularity until the period following the 1957-58 freezes when growers sought additional means of protection for their groves. In the ensuing years, numerous wind machines were installed in the citrus belt. The majority of these machines were in the 85 to 100-brake-horsepower group, powered by gasoline engines. The largest portion of these machines was commercially built, although a few growers tried to build and operate "home-made" wind machines.

There were 133 wind machines estimated to be in use in California for citrus in 1938 according to Adams (1). He reported that in 1952 the Agricultural Extension Service in California estimated the number of wind machines in use at nearly 2,800 machines. According to this report, there were, by actual count, 2,779 machines of 3 major types. The largest number, 1,561, were gasoline models. Electric models showed 1,018 followed by diesels at an even 200 machines. A large percentage of these wind machines were supported by supplemental heaters when heaters were required. In Riverside County over 88 percent of the wind machine acreage had supplemental heaters.

There is no up-to-date survey of the wind machines in Florida, but many were purchased and installed following the 1957-58 freezes. Hughes (54) reported in 1958 that 20 wind machines had been installed in Florida since January 1, 1957, bringing the total in the state to 30. On certain nights these wind machines were reported not effective. This was primarily due to wind mixing and lack of sufficient inversions.

## Heat Transfer and Balance

Heat Transfer in a Citrus Grove: All heat transfers that take place in the first 500 feet of the atmosphere must be considered in a study of cold protection in a citrus grove. Heat transfer can be divided into 2 categories: latent heat and sensible heat. Heat is generally understood

to be that energy which causes a body to change in temperature or undergo certain other related changes. In terms of kenetic energy, it is the energy associated with the motion of the atoms and molecules of the body, the greater the motion the higher the temperature. Temperature can be defined as the degree of hotness or coldness measured on a definite scale based on some physical phenomenon such as the expansion of mercury.

Sensible heat can be transferred in 3 basic forms according to Byers (27). The 3 methods of sensible heat transfer are radiation, conduction and convection.

Radiation is the movement of heat energy through space by means of electromagnetic waves without the aid of a material medium (27). The majority of this movement is carried on in the invisible range, especially in the infrared portion of the spectrum. Convection involves the transfer of heat by means of mass motions of the medium through which the heat is being transferred. This is possible only in liquids and gases because they alone have internal mass motions. In convection the moving masses of the medium carry with them heat acquired from previous locations. Convective motions can either be horizontal or vertical with the majority of movement in the horizontal plane. Heat conduction is the transfer of heat through a material medium that can be classified as a conductor. In any conductor where there is a temperature differential, the heat will tend to flow from the area of highest temperature

to the area of lowest temperature. Conduction in a citrus grove mainly takes place between the soil and plant parts and the air in contact with them.

The amount of energy or heat that can be radiated by a body depends directly on the temperature of that body. At any given temperature, there is an upper limit to the amount of radiation that can be emitted for a given time by a unit of surface (27). When an object is emitting the maximum amount of radiation possible at a given temperature, it is termed a "black body". This term is misleading in that it implies the concept of color. The object radiating does not necessarily have to be black but can be any color providing it is emitting the maximum radiation for a given temperature. A "black body" not only emits a continuous spectrum but also absorbs all radiation that reaches it.

Georg (45) stated that the earth, more specifically groves, trees, leaves, fruit and soil may be considered "black body" radiators for all practical purposes at wave lengths greater than 4 microns. That is, they emit a continuous spectrum that depends only on their temperature.

According to the Stefan-Boltzman law of radiation, the amount of heat radiated by a "black body" surface is proportional to the fourth power of its temperature, or in equation form:

$$R_b = \sigma T^4$$

where:

$\sigma$ is the Stefan-Boltzman Constant ($8.17 \times 10^{-11}$ cal.cm.$^{-2}$ $^{o}K^{-4}$)

T is the temperature in Kelvin degrees

$R_b$ is the "black body" radiation

The net outgoing radiation is the difference between the full radiation from the surface to space and the back radiation from the lower portions of the atmosphere according to Brunt (25) and Sutton (79). Some outgoing radiation is intercepted by moisture and carbon dioxide of the atmosphere and will be radiated back to the earth's surface.

Brunt (25) stated that the net radiation ($R_n$) is equal to:

$$R_n = \sigma T^4 - \sigma T^4(a + b + \sqrt{e})$$

where:

T is the surface temperature in degrees Kelvin

a is constant

b is constant

e is the vapor pressure in millibars

This equation is a theoretical analysis of the variation of surface temperature as related to the net radiation on a clear, calm night. He also considered the absolute humidity as an influence on net radiation but ignored the heating of the surface by the air or condensation of water vapor.

One should not interpret from Brunt's formula that $R_n$ is constant, Groen (50) pointed out, since the lower atmosphere seldom remains qualitatively the same throughout an entire night. He showed that a 21.6° F surface temperature change can result in a reduction of the $R_n$ from 0.150 to

0.090 gm.cal.$^{-2}$min.$^{-1}$ during the course of the night. Groen showed a simplified version of the Brunt equation where $R_i$ indicates the back radiation.

$$R_n = \sigma T^4 - R_i$$

Since solar radiation is lacking in the nocturnal heat balance studies, it does not govern the heat exchange as in diurnal studies. According to Geiger (39), the nocturnal heat exchange is almost solely dependent on the radiation from the earth's surface. This radiation is found mostly to be in the 10-micron range which can be classified as long wave infrared radiation.

Wang (88) stated that the "black body" radiation from the earth's surface can be calculated easily, provided you know the soil surface temperature.

Radiation alone does not account for the total heat balance of the surface according to Sutton (79), since there is an internal transport of energy by turbulent mixing and a transfer of heat from the surface to the atmosphere by evaporation and subsequent condensation at higher levels.

Georg (45) indicated that during cold weather in Florida, the higher the vapor content of the atmosphere, the less will be the fall of temperatures near the ground at night. This does not mean critical temperatures cannot occur with appreciable water vapor in the first 20-30,000 feet of the atmosphere because the water vapor is almost perfectly transparent from 8 to 13 microns, and this range covers the peak of the earth's radiation. Energy emitted

from Florida groves in this range passes unimpeded into space unless clouds formed of condensed moisture vapor are present to absorb and reradiate the terrestrial radiation.

Priestley (69) concluded that when heat is supplied or withdrawn from the intersurface between the air and the soil, the temperature behavior in the layers close to the surface is controlled by conduction rather than convection. Wet soils will produce 4 times the temperature response of a similar dry soil with the same heat supply. This is mainly due to differences in the conductivity of the soil rather than to the heat capacity.

Heat exchange in citrus orchards has been under study by Brooks et al. (23) in California since the early 1950's. In their paper they described radiation cooling to the sky, conduction from the ground, convection from overhead and also changes in phase of moisture present. The average outgoing radiation losses range from 22 to 25 British thermal units (Btu) per hour per square foot of surface. They concluded that approximately 75 percent of the heat loss would come from ground cooling, 8 percent from tree cooling and the remaining 17 percent from cooling of the air. Of the 75 percent from the soil, 40 percent would be directly to the sky from the soil, 20 percent by indirect radiation and 15 percent indirectly by convective currents to the tops of the trees.

The process of heat transfer was further outlined by Brooks et al. (17) by expressing the various types of

transfers in equation form on an hourly basis. They stated that the air supplies only one-fifth to one-quarter as much heat as the soil. A 9-year-old citrus tree cooling at the rate of $1^{\circ}$ F per hour provided about 10 percent of the total radiation demand. As the tree became larger with age, it was able to supply increased portions of the heat demand.

The authors stated that changes in phase of moisture are often a noticeable and measurable source of nocturnal energy. The heat evolved by lowering the dew point from 40 to $32^{\circ}$ F is approximately 8 Btu per square foot of an air layer 60 feet thick. If this lowering takes place over a 4-hour period, it is supplying about one-tenth of the radiation rate. In freezing the dew, the latent heat released is about 1 Btu per square foot. If this release occurs during a 1-hour period, it will counteract a $1^{\circ}$ F drop in air temperature.

Latent heat can be described as the flow of heat without any accompanying change in temperature (88). It is the quantity of heat required to change the state of substance after it has reached the temperature at which the change takes place. Such changes take place during evaporation, condensation and freezing. In this research we will primarily be concerned with those changes where heat will be released by the reaction.

Georg (44) concluded that the cooling of the atmosphere starts at the earth's surface and that this surface plays a major role in nocturnal heat exchange. The rate of heat

conduction either downward or upward within the soil depends on the existing temperature gradient and the soil heat conductivity. Heat conductivity can be defined as the heat in calories that can pass through an area 1 centimeter square if there is a 1 degree Centigrade temperature gradient perpendicular to the cross section with no lateral heat loss taking place. This can be expressed in the following equation:

$$W = \lambda\left(\frac{dt}{dx}\right)$$

where:

$W$ is the heat passing through a square centimeter

$\lambda$ is the soil conductivity

$\frac{dt}{dx}$ is the vertical temperature gradient

Georg concluded that W can be increased by changing the value of $\lambda$. This can be accomplished by wetting the Florida sandy soils. By wetting the soil, the thermal conductivity would increase from 0.0004 cal. per $^{o}$cm. sec. to 0.004 cal. per $^{o}$cm. sec. In addition to this change, the surface albedo is changed thus reducing the reflectivity. He suggested wetting the soil before the freeze and allowing the surface to dry to reduce evaporative cooling. The specific heat of the soil is also changed in that it will take more heat per unit area to warm up the soil. The reverse of this is also true. The soil will give up more heat per unit area with less drop in temperature.

Brunt (25) wrote a formula for surface cooling and heat transfer in the upper layers of the soil. The atmosphere

was effectively eliminated from the equation so that only the soil was considered. His formula also requires that all the soil layers be at the same temperature or uniform throughout at the start of the measurements. This will give a heat flux of 0. Brunt's cooling equation is stated:

$$T(0,t) = T_o - \frac{2R_n}{P_1C_1K_1}\left(\frac{t}{\pi}\right)^{\frac{1}{2}}$$

where:

$P_1$ is the soil density

$C_1$ is the specific heat of soil

$K_1$ is the thermometric conductivity of soil

$T$ is the surface temperature in degrees Kelvin

$R_n$ is the net radiation

$t$ is time

$\pi$ is 3.14

Heat Balance in a Citrus Grove: The heat budget or heat balance is made up of all the various components which involve heat transfer in the area under study, specifically, in this instance, the first 50 feet of atmosphere above the earth's surface.

Gerber and Decker (47) described the heat budget equation as follows:

$$H = A + E + S + \ldots.$$

where:

H is the heat remaining at the surface after radiation processes

A is the sensible transfer of heat to the air

S is the heat used in heating the surroundings, usually the surface

E is the heat used in evaporation

The heat balance equation is stated in a slightly different form but with basically the same components by Wang (88).

$$R_n = Q + L + G + e$$

where:

Q is the sensible heat flux

L is the latent heat flux

G is the heat stored in the ground

e is an error term

Brooks et al. (24) took the same parameters in more detailed form and wrote them into a heat balance for the citrus orchards of California.

$$E_{ru} = -C_1 k\left(\frac{dt}{dz}\right)_s - C\gamma K\left(\frac{dt}{dz}\right)_u - C_2\gamma C_p W_o\left(\frac{dt}{d\theta}\right)_o$$

$$-C_3 \lambda_t W_d\left(\frac{dt}{d\theta}\right)_o - C_4 C_e \lambda\left(\frac{dW}{d\theta}\right)_{se}$$

where:

| | |
|---|---|
| $C_1, C_2, C_3, C_4$ | is the coefficient to adjust for irregular areas |
| $C_e$ | is the correction coefficient for temperature |
| $E_{ru}$ | is the net radiation |
| k | is the average thermal conductivity of soil |
| K | is the average eddy diffusivity |
| $\left(\frac{dt}{dz}\right)_{s,u}$ | is the average temperature gradient in soil or air |
| Cp | is the volumetric heat capacity of the soil |

| | |
|---|---|
| $W_{d,o}$ | is the effective weight of substance per unit ground area either dew or orchard trees |
| t | is the latent heat of vaporization |
| $\theta$ | is time |
| se | is the surface evaporation |

This same equation can be expressed more simply in the following terminology:

$R_n$ = Soil Heat + Downward Convective Transfer + Heat from Trees and Air + Latent Heat + Soil Evaporation Heat

Many other equations have been written including those of Brunt (25), Turrell and Austin (84) and Raschke (71). Most of these equations were written with specific applications in mind; thus each will vary somewhat in the components used to make up the equation. There are many terms that can be introduced into the heat balance equation, but most of these are very small quantities that have little or no significant bearing on the final result.

Many heat balance equations have been used with satisfactory results, probably due to the fact that only the major parameters have been used. These major parameters are so large in magnitude compared to the lesser parameters that they override the effect the lesser components might show. The minor components are often extremely difficult to obtain and in many cases are approximations. Being difficult to obtain accurately, these small values can introduce many errors into the equation. Rather than introduce these errors, many researchers choose to ignore the smaller components.

The major components of heat balance are net radiation, soil heat flux, latent heat flux and heat flux of the air. Some minor components are metabolic heat releases by plant tissue and heat stored in plants.

For purposes of wind machine evaluation, the heat balance equation may be written in its simplest form as:

$$Cp\frac{dT}{dt} = R_n + A + S + LE$$

where:

Cp is the heat capacity of air

dT is the change in temperature

dt is the change in time

$R_n$ is the net radiation

A is sensible heat stored in air

S is heat stored in soil

LE is latent heat of evaporation

In order to obtain protection, the heat gain must be equal to the heat loss. If this is true, then Cp does not have to be known because the change in temperature with relation to the change in time would equal zero. If the heat input by the wind machine is equal to the sum of the other values, then the equation would read:

$$I = R_n + A + S + LE + K$$

where:

I is the input of heat by wind machine

K is the convective heat transfer

If we place the grove in an imaginary box (Fig. 1), we can diagram the above equation.

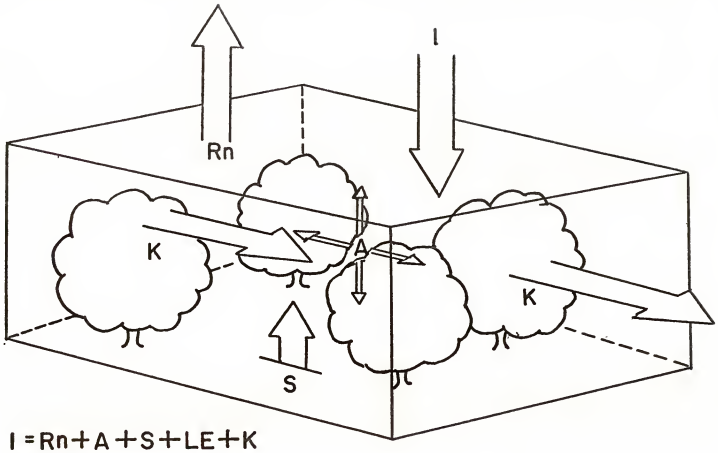



Figure 1. Grove enclosed in an imaginary box. Marked arrows indicate the various heat losses and gains.

## Theory of Wind Machines

Meteorological Aspects: The principle of cold protection by wind machines is based around the natural phenomenon of the nocturnal temperature inversion. This natural phenomenon has been known to meteorologists for many years. A detailed explanation and discussion on the formation of nocturnal temperature inversions can be found in almost any good meteorological text such as Geiger (39) or Brooks (13).

An inversion is not only dependent on the heat balance, but it is also dependent on the adiabatic lapse rate. The adiabatic lapse rate is approximately 1.8° F for each 100 meters of vertical air movement according to Priestley (69). As a parcel of air changes position in the vertical profile, it may be expanded or compressed by the pressure of the atmosphere above it. If this expansion or compression occurs without the air giving up or receiving heat from the surrounding air, the change is said to be adiabatic.

Briefly, the ground-radiation type inversion or nocturnal inversion is formed under conditions of little or no horizontal convection movement during the hours of rapid cooling of the earth's surface by radiation. The ground being cooler than the air in contact with it removes heat from the air by conduction, and the air near the surface becomes colder than the air a few feet above. As time progresses, this layer of cool air builds up, and as a result, the temperature increases with height provided no convective mixing takes place.

Young (91) in 1920 described the rate of increase of temperature with height on radiation nights in orange groves in California. He stated that the temperature continued to increase with height to distances of 300 to 800 feet. Above this point there was a gradual decrease in temperature. Temperatures above 300 feet were stable, and no change could be noted after 7 PM. Young concluded that the difference in temperature between the ground and 100 feet depended almost entirely on the amount of temperature fall at the ground level. He stated that the rate of fall was greater following a warm day than a cool day. Also the rate was greater on a dry night than on a moist night.

The wind machine is one means of mixing air in the first 50 feet above the soil surface. Brooks (11) compared the wind machine to a nozzle that delivers warm air from an inversion in the form of an air jet which creates eddy currents in and about the citrus tree. Cold air among the trees is entrained and mixed with the warmer air of the jet thus modifying the temperature nearer the surface.

In 1912, McAdie (63) wrote on the influence of air mixing for frost protection based on the utilization of a nocturnal temperature inversion. The value of mixing the lower portions of the atmosphere to modify the cooling influence exerted by radiation near the earth's surface was indicated by Humphreys (56). Temperature inversions were shown by Baker (9) and Young (92) to range from 5 to 10° F in the first 40 feet above the California soil surface.

Frith (35) reported on inversions in Australia ranging from 5 to 14° F in the lower 300 feet of the atmosphere. The greatest portion of this increase was noted in the first 100 feet.

The wind machine does not add any heat to the grove but simply makes the heat already present in the air more available to the trees according to Gerber (46). He stated that temperatures 50 feet above the ground may be 5 to 10° F warmer than at 10 feet above the ground. Wind machines mix this warmer air stored at 50 feet with the colder air around the trees. The net effect is to slow the rate of temperature fall and maintain the temperature higher than the surrounding unprotected areas.

Theory of Wind Machine Operation: Brooks (20) stated that the wind machine propeller sets in motion a stream of air that can be considered a free jet until it reaches the tree tops. The outline of the jet is a cylindrical cone with the propeller located in the cone about 3-propeller diameters from the apex. The included angle of this cone is about 24 degrees and is dependent on the origin of the jet such as a nozzle or propeller. The cross sectional area of the jet increases directly as the square of the distance. Therefore, the volume rate of flow increases directly with the distance. Since this increase in volume rate of flow must come from the surrounding air which is drawn into and mixed with the rest of the air in the jet, a free jet is a good mixing device.

The turning jet has also been studied in California by Leonard (62). To move the air transversely to its axis induces a shearing effect that greatly retards the outward flow of air. In such a case, instead of the jet velocities decreasing in direct proportion to the distance, as is true of stationary jets, the velocity in moving jets ultimately decreases approximately as the arithmetical square of the distance. If the jet is turning, the retardation increases with the distance so that the velocity decrease of the ultimate expanding ring would be as the cube of the distance. In tests, the time of arrival of the jet at 400 feet varied considerably and at times was not recorded at all. Apparently the jet was being bent to such an extent by natural air flow and eddy currents, it never reached the recording tower.

In his explanation of the turning jet, Leonard (62) described it as an ever expanding toroid or an expanding circle rotating about a straight line in its own plane, and he proceeded to combine the laws of the stationary jet and the expanding toroid into 1 set of equations. The air moving away from the propeller tends to have considerable lag as the wind machine moves through its cycle. The machine after completing 1 revolution produces a second new jet cone inside the first one from the previous revolution. As the second toroid proceeds away from the machine, it eventually makes contact with the first and merges rapidly into 1 jet. This process continues on with each successive

toroid joining those previously formed. As this more or less circular system of toroids pushes outward from the wind machine, it opens a hole in the cold air near the ground. As long as the machine continues to run, the hole can be maintained by the outward force of the moving air. The outward portion of the turning jet is influenced greatly by air drift since it is the slowest moving portion and can be deflected easily.

Mean airflow and heat transport patterns with relationship to wind machines were studied by Baker (8) in 1955. He compared the action of the free jet with the action of a wind machine jet. For a wind machine to modify the air temperature, warm air must exist in the upper air layers. The author presented the theory of the expanding jet similar to the previous discussion by Brooks et al. (21) but from the basis of a stationary jet rather than a turning jet. As the air is projected outward from the fan blade, new air in the surrounding area is drawn into it, increasing the size of the jet cone; thus an expanding jet is formed. With relation to the heat transport pattern, the author stated that the theoretical thermal response at a point in the modified area of the citrus grove would be approximately 35 percent of the existing difference in the temperature of the air at blade height and that at ground level. The modification would by no means be isothermal due to topography and plants which would alter the airflow of the jet.

In 1956, Ball (10) authored a paper dealing with

convective mixing through the use of a frost fan or wind machine. The theoretical development is of a highly technical nature, but 2 very interesting conclusions are reached. Only one-fourth of a horsepower is required per acre to sufficiently mix the air in the 30 meters next to the ground for frost protection. The mixing requires 2 types of operations: (1) small eddy currents generated by a large, slow-moving jet to achieve isothermal conditions by mixing and (2) a small-diameter, high-speed jet to give penetration to a reasonable distance from the fan. Condition (1) can be satisfied with a large-diameter, slow-moving propeller whereas condition (2) can be met by a small, high-speed propeller. He concluded that a great deal of horsepower now required for adequate protection is being wasted in shaking trees, blowing sand and in frictional conversion of mechanical work to heat. He estimates 6 horsepower per acre is dissipated by viscous forces, and this force is equivalent to the viscous forces dissipated by the natural wind moving at 5 meters per second. The rate of gain from this dissipation is only about one-hundreth of the rate of heat loss caused by ground cooling and is therefore relatively insignificant where dealing with frost protection. Ball estimates that the majority of the wind machines in use today in the United States require an average of 12 horsepower per acre.

Halstead and Covey (51) observed that mixing did not depend on the wind speed but rather on the rate of change in

wind speed relative to height. They equated a mathematical model for convective heat transfer as follows:

$$Q_{conv} = - 1/3PCp\ Vc/V(U_{2z} - U_z)\ (T_{2z} - T_z)$$

where:

| | |
|---|---|
| $Q_{conv}$ | is the convective heat flux |
| P | is the density of air |
| Cp | is the specific heat of air |
| Vc | is the thermal conductivity of air |
| V | is the viscosity of air |
| $U_z$ | is the wind speed at height z |
| $T_z$ | is the temperature at height z |

## Results of Wind Machine Tests

Australian Wind Machine Research: The first report of wind machine tests in Australia was published by Shaw and Redlich (75) in 1946. The machine powered by a 5-brake-horsepower (bhp) motor was mounted on a 12-foot tower with a 12-foot blade. This fan was horizontal and blew a blast of air vertically downward to the ground where it spread over the surface. The results were promising even though the area protected was small.

Redlich (72) continued with similar type machines of low horsepower turning horizontally with the ground. He increased the tower height to 15 feet using the 12-foot propellers and then went to a 21-foot blade with a 12-bhp motor. He determined from this work that it required about 5 bhp to mix the air over an acre up to 25 feet high. He

obtained a 2° F rise over an area of 1 acre with his wind machine.

In 1948, Frith (35) built and tested 2 wind machines mounted on 25-foot towers in Australia. One machine was powered by a 10-hp electric motor and the other by an automobile engine. He used a horizontally mounted, 21-foot fan blade with a blade angle of 14 degrees turning at 147 rpm. The maximum temperature rise was 12° F with an average between 5 and 6° F being recorded. Such rises only occurred under conditions of moderate to strong inversions. The range of the relative effect of the fan was found to be inversely proportional to the magnitude of the temperature difference that existed between the air delivered by the fan and the temperature of the air close to the ground. The temperature of the air delivered by the fan was proportional to the degree of the temperature inversion that existed. Under conditions where the 5 to 6° F modification was observed at the tower base, only a 1° F rise was recorded at a distance of 150 feet. Drifts of 2 mph or greater were able to displace the affected area considerably in the direction of the drift. Later, when the skirts of the trees were removed, the area of protection, 1° F, was increased from 1.73 acres to 2.16 acres. The range of effect of the fan in citrus and almonds was studied by Frith (36). He reported that the density of the foliage of the 2 crops caused appreciable differences in the fan's zone of influence. The area in citrus was less than in almonds.

Angus (2), in analyzing previous work done in Australia, felt that the horizontal fans using low horsepower input were successful in moving air down but lacked sufficient lateral movement and proper eddy current mixing. He stated that the American type machines with the vertical fan and high horsepower distributed and mixed the air well but lacked efficiency in pulling warm air down from the upper air layers. Angus (3) changed from the horizontal fan to a fan tilted at 62 degrees and found he could produce a 2° F temperature rise over 1.24 acres. The machine rotated 360 degrees in approximately 1 minute using 8 bhp per acre.

Frith (37) reported on the results of a dual-mounted wind machine on a 35-foot tower which rotated 360 degrees every 7 minutes. Each wind machine was powered by a 40 bhp motor that turned 12-foot airscrews at 635 rpm. The motors were mounted on cradles so they could be tilted from 0 to 20 degrees as desired. Tilting of the blades led to a significant increase in coverage. Tilts greater than 7 degrees and up to 20 degrees gave no significant further variation in the area covered. With both motors horizontal, the area covered was small and markedly influenced by natural drift. Results indicated that the 7-minute rotation was ample to maintain temperatures throughout the cycle and that even a slower speed might be satisfactory. The Australian machine was effective in raising the orchard temperature 2° F over an area of 10 acres with power

expenditures of 12 bhp per acre. This was comparable to the California type wind machine.

Angus (4) showed that there was a significant rise in temperatures in a grape planting when a wind machine was used for frost protection, provided a moderate temperature inversion existed. The wind machine was stopped several times during the nights when it was in operation, and each time a substantial rise in temperature was recorded when it was started again.

When comparing the work of Frith (37) with his own, Angus (5) concluded that a tilt of 70 to 80 degrees from the vertical appeared to be optimum. In terms of the American researcher, this would be 20 to 30 degrees depression from the horizontal. He suggested the most efficient performance would be obtained by dividing the total power available among several smaller machines rather than putting it into 1 or 2 large machines. He based this recommendation on the fact that performance did not increase linearly with the power input and the increased value by overlapping several machines as a unit. The area of protection varied as the cube root of the power consumed in operating the wind machine. Angus felt that the smaller units gave more consistent performance and distribution.

Angus (6) presented an excellent summary of the past research in Australia and the research that is presently in progress. He concluded that certain criteria should be kept in mind when designing wind machines. The turbulent eddy

size of the jet should be relatively small; a propeller at a greater height will be more effective provided it has the power to penetrate to the ground level; a group of small machines will give more consistent results than 1 large unit. He reported, however, that wind machines do not protect dense, low-growing crops, and their usefulness is limited by their marked dependence on the inversion strength.

Angus pointed out that: (1) the performance of the wind machine varies markedly with the strength of the inversion, (2) the penetration of the jet is greater with the drift than against it, (3) the air jet should be directed slightly downward between 10 and 20 degrees below the horizontal, (4) the area covered by the machine increases as the rotation speed is decreased and (5) the size and speed of the air jet determines its penetration which is mainly controlled by buoyancy.

California Wind Machine Research: California growers became interested in air moving machinery after Young (92) published information on inversions. Young (93) in 1924 reported on 4 of these early machines designed by citrus growers. Pictures and descriptions were published in his article. None of these designs are in use in the United States at the present time.

In 1928, Johnston (58) wrote that wind machines were effective in warming the air close to the ground a few degrees when inversions were present. The fruit and leaves were maintained more nearly at the air temperature when the

wind machine was in operation. Because the fruit remained dry for a longer period of time, it undercooled.

Moses (64) determined a 75-horsepower wind machine on a 40 to 50-foot tower was capable of giving protection of approximately $3^{\circ}$ F over a 10-acre area when the existing inversion was $10^{\circ}$ F. Wind machines were classified by Schoonover et al. (74) as large or small according to the coverage obtained. The small model had a circular coverage 600 feet in diameter whereas the larger model covered an area 1,000 feet in diameter.

It was reported by Brooks et al. (16) that wind machines were able to modify orchard temperatures 1 or 2 degrees but were not able to stop the natural cooling process. They stated that the loss of heat by radiation to a clear, cold sky measured at Riverside, California, was in the range of 20 to 25 Btu per hour for every square foot of ordinary surface such as soil or citrus foliage. They predicted that it was probable that a large number of wind machines, approximately 1,000, would prove inadequate due to the fast indrift of cold air. Furthermore, there was no expectation that wind machines could afford protection when there was a freeze with cold daytime conditions, cold soil and relatively no warm air overhead on a clear, cold night. They stated that wind machines add no heat themselves and heat gain is due to forced convection; thus the machine should not be started until the critical point is reached. The response will be greater with the drift than against the drift with a wind machine in operation.

In 1949, Brooks (12) estimated that without a strong inversion more than half of the artificial heat promptly rises above the trees. Only half of this heat gets back by diffusion and radiation. The wind machine would increase the recovery percentage by forced recirculation.

Brooks et al. (22) showed that there was a gain of 20 to 30 percent in temperature response using wind machines and heaters together over and above the sum of the separate responses. Conclusions indicated 8 to 12 heaters per acre gave a substantial boost in temperature response. Thrust measurements were taken on the wind machine in the same test. The tests indicated that when the wind machine was blowing with the drift, the thrust measurement decreased only 2 percent for a change in drift velocity from 2.3 to 3.5 mph.

Protection was obtained by Yarick (90) even though there was no recordable evidence of a temperature change. He explained that the protection offered by the wind machine was due to the air movement reducing temperature differences at various levels within the tree. The pattern of protection produced by the wind machine was similar to a doughnut, having a cool area in the center. Across the drift pattern, the temperature rise was equal, but with the drift it was somewhat elongated on the down drift side and was shortened on the up drift side.

Significant responses from wind machines depend directly on the temperature inversion strength according to

Brooks et al. (23) since the heat supplied by the machine itself comes solely from the heat generated by the power plant. The temperature at 40 feet above the surface was lowered after the wind machine was started whereas the temperature below this point was raised. This lowering does increase the temperature gradient, tending to bring more heat down by eddy convection from higher elevations.

Tests were run comparing groups of 15 bhp and 90 bhp by Brooks et al. (17, 18, 19). They reported that the smaller machine does not have enough power to take full advantage of strong temperature inversions. They estimated it would take 3 15-bhp wind machines to produce the same results as 1 90-bhp wind machine.

In 1952, Adams (1) reported the range for starting wind machines was between 27 and 32° F with the most popular being 30° F. He suggested using a 32° F starting temperature in lemon orchards.

The best design for a fan was determined by Brooks et al. (19) to be a 2-bladed propeller of sheet metal construction relatively narrow for its length with a moderate amount of taper near the tip. The design of such a blade should have a low-cambered, low-drag airfoil.

Brooks et al. (21) continued testing multiple wind machine installations and determined the 15-bhp machines should be spaced 550 feet apart, parallel to the line of normal drift and 400 feet apart in the transverse line to the drift. The 2 machines on the up drift side operated

more or less as isolated machines whereas the down drift machines strongly influenced each other, maintaining a large warm belt between them. The 70-bhp wind machines were set considerably farther apart, 700 feet by 900 feet. Again the 4 machines produced a similar pattern to the smaller machines.

In 1955, Rhoades et al. (73) studied the conventional American type machine in the almond orchards of California. While observing the inversion formation, the authors discovered the inversions seemed to increase in strength as the leaves developed on the almond trees. They felt that since the leaves and branches cool directly by radiation to the clear sky, the increase in leaf surface provided a greater contact area for cooling the air below 50 feet. As the foliage thickened in the tree tops, it tended to prevent warmer air which was drifting over the orchard from moving down and mixing with the cold air which had settled between the trees. Inversions were generally less than those found in citrus orchards, and the protection was accordingly less. The area of protection of the wind machine was smaller than the area found in citrus research. The authors concluded that the difference in the planting systems was partially the cause of the reduced coverage.

Brooks and Leonard (14) conducted tests with various frost protection devices in deciduous orchards and concluded that the temperature inversion is important to all types of frost protection, especially the wind machine. They felt

that wind machines would help any type of heating system by giving better distribution except in the case of irrigation where the heat release is very small. Wind machines cannot be expected to give adequate protection under conditions of weak inversions unless supported by heaters.

Early starting of the wind machine, according to Turrell et al. (85), brings down warm air from the inversion layer and slows the cooling of the fruit and leaves so that the period of critical temperatures is of shorter duration. Even though it may not be possible for the wind machine to bring warm air down the inversion layer, the moving air is beneficial because it raises the temperature of the exposed plant parts looking into space, which are cooler than the surrounding air. The operation of the wind machine after sunrise hastens the warming of shaded fruit and slows the warming of exposed fruit in the sunlight.

Brooks and Schultz (15) presented data on comparative operating costs of heaters alone, wind machines alone and wind machine and heater combinations. They stated that costs have been greatly reduced by the use of wind machines which in general reduce the number of heaters to one-third and reduce heater hours of operation to about one-sixth. Operating costs including maintenance for heaters alone was $100.00 per acre whereas using the wind machine with heater support only cost approximately $30.00 per acre. Initial installation was greater with the wind machine and support heaters than with heaters alone. The authors used a dual

machine sending out jets of air in opposite directions at a 7-degree depression angle and a tower rotation speed of once every 8 minutes. They found that the outward flowing air lagged so far behind the axis of the propeller that the jet was advancing outward almost broadside as an expanding toroidal ring. The size of the spiral was decreased as the turning speed of the jet increased. Results with a heated jet were disappointing because of the increased buoyancy which lifted the jet above the orchard.

In describing the action of the wind machine on the fruit, leaves and trunk, Turrell (81) stated that distance was the principal factor in a wind machine's effectiveness and distances beyond 500 feet from the machine base using a 110-bhp unit showed little or no protection.

Brooks et al. (24) tested blowers above the tree tops and under the tree canopy with heat added directly into the jet. The temperature profiles demonstrated that by adding large amounts of heat to the cone, the jet lifted itself over the tree zone. They found when heat was added, the area of moderate protection decreased as did the total acreage protected, but the degree of protection was increased close to the wind machine. The buoyancy effect found is a serious disadvantage to adding heat to the jet near the fan. The authors found that heat added by use of heaters scattered throughout the grove area was more desirable and beneficial. They developed a force balance interpretation of the jet action against the inflow tendency of

the surrounding cold air. Multiple wind machine installations take advantage of this principle and give better protection.

Turrell and Austin (82) made a study of the conditions existing in groves that influenced wind machine operation. The amount of protection was found to be proportional to the number of factors found in any particular grove. They listed 6 factors for consideration: (1) if the grove had been irrigated regularly prior to the cold, (2) if irrigation water was standing in the furrows during cold nights, (3) if the ground surface was moist, (4) if large wind machines were in use, (5) if heaters had been lit and (6) if a strong inversion was present.

Research by Crawford and Leonard (30) indicated that blowers located among the trees generated more turbulence in the tree zone whereas the overhead machines generated more turbulence above the trees and only among the trees where it could penetrate the canopy. A 6-foot propeller was the largest practical since an increase in thrust caused damage to the trees. They suggested placing 1 row of heaters in the border row all the way around the orchard and a second row several trees inside the first row. The number of heaters per acre in this method would be less than with a single wind machine mounted on a tower.

Adequate power is necessary, Turrell _et al_. (83) stated, to "punch a hole" in the dense, surrounding cold air. The wind machine lowers the pressure around the

machine base. This lower pressure and gravity then bring the warmer air from higher elevations down for circulation over the grove.

Testing in California by Brooks et al. (21) demonstrated that 2 or more wind machines spaced to permit overlapping of patterns produced complementary action. They studied the influence of propeller diameter on the overall cost of frost protection and concluded that larger diameters than those in use at that time would be more economical. These larger machines would be more expensive initially due to the larger propeller with its necessary gear reduction to provide a slower turning speed, but there would be a saving in power and demand charges. This larger propeller would also reduce the noise during operation.

Florida Wind Machine Research: The earliest research attempted with a wind machine was done prior to 1957 by Georg (40, 41). Working with Lake Garfield Nurseries, Georg conducted tests with electric wind machines with an overall propeller length of 7 feet. These were mounted on 30-foot masts. Beginning in 1957-58, tests were started with 6 gasoline model machines with 11-foot propellers. These were mounted on 26-foot masts and turned at a slower speed than the electric models.

Georg reported on his early investigations and concluded that the degree of protection depended on 3 conditions: (1) the velocity of the natural wind, (2) the nature of the vertical temperature structure and (3) the actual

values of the temperatures composing the vertical profile. Wind machines provided the most protection under relatively calm conditions with a good inversion and when the air 28 feet above the surface had temperatures above the freezing point. When natural wind speeds reached 6 mph, there was little or no protection afforded by the wind machine.

Georg (42) found that wind machines did not destroy the inversion 270 feet from the wind machine as anticipated, and the stability at tree height of the air was most difficult to break down on occasions. This could be partially due to the roughness height of the orchard and the distance from the wind machine to the measuring point; but he concluded a third factor, the air density, was also important. The air density is a function of the specific humidity, air temperature and atmospheric pressure. The author felt that this aspect of the wind machine needed further study.

"Roughness height" was explained by Geiger (39) as the height where a cover crop retards the convective movement or wind and causes a change in the direction of the wind away from the prevailing direction. The vegatative cover crop can exert a considerable influence on the convective turbulent mixing near the surface. He showed the influence of trees on turbulent mixing. In pine trees 15 meters tall, the wind speed was 1.61 meters per second near the tops whereas at 4.25 meters, it was only 0.69 meters per second. He also presented evidence of the influence of leaf growth on wind penetration. There was greater penetration without leaves on the trees than with leaves present.

In 1959, Hughes (55), reporting on Florida research, stated that growers should start their wind machines when the temperature at the top of their towers reached 40° F. He also stated that once the machine was started, it should not be stopped until the temperature is above the danger point. The wind machine will not give protection in winds over 6 mph.

Results with a 25-bhp electric wind machine in a grapefruit grove and a 60-bhp machine, gasoline powered, in a citrus nursery were reported by Georg (43). In these studies he emphasized the fact that the protection down drift from the machine was greater than in the area up drift. Since the direction of the drift may not be the same on all cold nights and may frequently change or vary during any given night, it follows that the protection pattern will change as the drift direction shifts.

Wallis (87) concluded that 2 of the principal benefits from the wind machine are the turbulence of the initial blast and the eddy currents that remian long after the main blast has passed over. He felt that the main blast of air serves to distribute the moisture evenly over the area of protection and eddy currents prevent heavy moisture build up on the leaf surfaces between blasts. This action by the wind machine helps to prevent dew and frost formation.

Placement of a wind machine in a 10-acre-square grove was outlined by Griffiths and Hendershott (49). The machine should be located 100 feet from the northwest corner of the

square. They also reported that dual-headed wind machines in tandem operation probably cover very little, if any, greater area than a single-headed machine.

Wind machines and heaters used together provide the most efficient and effective cold protection under all types of conditions according to Gerber (46). The heaters are used to increase the air temperature and to supply radiative heat directly to the plant surfaces. The wind machine is used to disperse the heat uniformly over the area of protection.

Busby (26) working with peaches in Florida concluded that wind machines of the 100-bhp class will provide $2^{\circ}$ F protection over 8 to 10 acres on clear, calm nights. He stated that this not only represents a reduction in minimum temperature but also reduces the number of hours of low temperatures. Busby also discovered that the machine does not provide as much protection if it is not receiving the proper power input from the engine. The protection pattern in peaches was almost circular, and distortion by wind drift was not pronounced.

Wind Machine Research in Other Areas: In 1963, Young and Peynado (94) tested wind machines and return stack heaters in Texas. They reported the wind machine reduced the quantity of frost already formed on portions of the tree exposed to the direct blast. Considerable frost remained on the sides of the trees away from the jet blast. The average area of influence by the wind machine was 8.1 acres

with an average of 2.0 acres above 32.0° F. The effectiveness of the wind machine was found to decline near daylight when temperature inversions at 40 and 60 feet decreased from 4.2-5.0° F to 1.5-2.0° F. The authors also found that the leaf temperatures were very similar to air temperatures with the wind machine operating.

Hilgeman and Dunlap (53) in Arizona concluded that wind machines produced a gain in temperature of approximately 60 percent of the inversion at 60 to 120 feet down wind from the machine and about 30 percent of the inversion at 300 feet down drift. They also reported a cold zone developed frequently in the center of the 4 machines they were operating. The inversions in the test area averaged 7° F over a 15-year period with the strongest inverions occurring on moderately cold nights. Inversions on extremely cold nights tended to be weaker than those on moderately cold nights.

Priestley and Ball (70) studied the influence of heater plumes on the jet produced by a wind machine. They have shown theoretically that when plumes from adjacent heaters merge, the buoyant force is more than doubled. Thus, if heaters are to be used in conjunction with wind machines, they should be placed in such a pattern as to insure the plumes will not merge. If the plumes do merge, they will have a tendency to lift the wind machine jet above the trees and lessen the effectiveness of the machine.

Prototype Wind Machine Research: During the past few years, several new types of wind machine models which cannot be called standard models have been developed. These will be reported in this section.

Brooks *et al*. (20) in 1953 tested a 3-bladed helicopter wind machine and found that the response was good but the area covered by a 2° F rise was much smaller than with the conventional type wind machine. The machine had a vertical shaft with 3 10-foot blades each set at 45 degrees above the horizontal. With a 12° F inversion, the machine showed an 8° F rise near the tower base and a 2° F increase over 0.75 acre. This meant an input of 24 bhp was required to produce a 2° F rise over an acre. Strong inversions of 12° F or more did not increase the area modified as one might expect. This was apparently due to the increased tendency of the warm air to rise rapidly over the cold surface air. A sharp angle of upward flow was noted 50 to 70 feet from the wind machine, showing that the warm air was rising up over the orchard.

Preliminary tests were run with an experimental model of a ramjet rotor wind machine by Brooks and Leonard (14). The ramjet was depressed 15 degrees from the horizontal and made a 360 degree rotation once every 7 to 8 minutes. The principal difference between the ramjet rotor and the conventional fan is the means of supplying power to turn the propeller. Instead of using an electric or gasoline engine, the machine was driven by 2 ramjet pods mounted on the tips

of the propeller. Fuel consumption was high, but heat was added to the air jet by the motors. They felt that this machine warranted further attention.

Heat added by the ramjet was found by Goodall et al. (48) to be beneficial, but the noise produced appears to be a limiting factor to its widespread use. There was some evidence that a tall cover crop in the orchard reduced the effectiveness of the wind machine in raising the temperature in the lower portions of the trees. The ramjet was able to give a $1^{\circ}$ F rise over 14.1 acres with a $7.5^{\circ}$ F inversion and a $3^{\circ}$ F rise over 4.6 acres. With only a $1.4^{\circ}$ F inversion, the ramjet gave a $1.0^{\circ}$ F rise over 1.73 acres.

Under-the-canopy tests by Crawford and Brooks (29) were carried out in peaches during 1959. The primary reason for this type of testing was the failure of tower mounted machines to penetrate the tree canopies. These blowers without supplemental heat gave mixing beyond 210 feet without any rise of the jet. When heat was added by means of 2 propane burners, there was an increase in protection near the machine, but the jet rose before reaching the 210-foot checkpoint. They did not feel that the gain close to the wind machine was worth the additional equipment and fuel costs. The machine which was used was a 92-bhp model turning 2350 rpm with a $360^{\circ}$rotation every 5 minutes. The heaters added 4 million Btu per hour.

Sled-mounted, portable, under-the-tree blowers were tested in California by Crawford and Leonard (31). They

found that when large amounts of heat were added to the jet, the jet had a tendency to lift off the ground close to the machine. This could be overcome to some extent by increasing the thrust which in turn carried the jet further before it became buoyant. Multiple installations of small machines spaced close enough to overlap proved more effective than single machine installations.

## Heat Sensors

Thermistors: The word thermistor is taken from the term "thermal resistor" and is itself a resistor of high negative temperature coefficient properties. Thermistors are semi-conductors of a ceramic nature that are manufactured by sintering mixtures of metallic oxides of various conductive metals such as manganese, nickel, iron, cobalt and copper. When these mixtures are treated and fused, they take on the high negative coefficient properties. As the temperature of the thermistor increases, the resistance becomes less. When the temperature decreases, the resistance in the thermal resistor increases.

An expression relating the resistance and the absolute temperature (33) is as follows:

$$\frac{R_o(T)}{R_o(T_o)} = e^{\beta\left[\frac{1}{T} - \frac{1}{T_o}\right]}$$

where:

$R_o(T)$ is the resistance at absolute temperature T

$R_o(T_o)$ is the resistance at absolute temperature $T_o$

e is 2.718

$\beta$ is a constant depending on the material used to make the thermistor

Caution must be taken to insure that the very small voltage applied to the thermistor does not heat it above the ambient temperature and thereby reduce its resistance (33). If no heating occurs to raise the thermal resistor above the ambient temperature, then Ohm's law will be valid and the current will be proportional to the voltage applied to the system.

Thermistors have several advantages over other types of measuring devices used for recording temperatures. The greatest advantage is its sensitivity to temperature changes, more than themocouples or other similar devices (33). With the thermistor, there is no need to maintain a reference junction as required with the thermocouple. The high impedence for all practical purposes eliminates any resistance problems in the circuit design, allowing any length of lead wires to be used. Platt and Wolf (67) also stated that temperature coefficients of most resistors at $25^{\circ}$ C will vary from -3.4 to -4.4 percent.

## METHODS AND INSTRUMENTATION

### Research Site Description and Location

The wind machine research project was carried out in the W. R. Brown, Jr. citrus grove located southwest of Orange Lake in northern Marion County, Florida. Fig. 2 shows the location of the research site relative to the main areas of Florida citrus production (34). The terrain surrounding the immediate region of the grove site was undulating forested and cleared areas. Fig. 3 shows diagramatically the area immediately around the Brown grove site.

The grove site was considered to be high ground by weather forecasters, being situated on the crest of a hill with natural air drainage in all quadrants. The portion of the grove used for this research had air drainage to the south and west. The northeast corner of the test block had the highest elevation, and the southwest corner had the lowest elevation.

The research block was planted to mature 'Parson Brown' orange scions (*Citrus sinensis*, Osbeck.) budded on sour orange rootstock (*Citrus aurantium*, Linn.). The trees were planted in a square planting system, 25 by 25 feet. The mature trees were interspersed with replants which were placed in the grove following the 1957-58 freezes. The

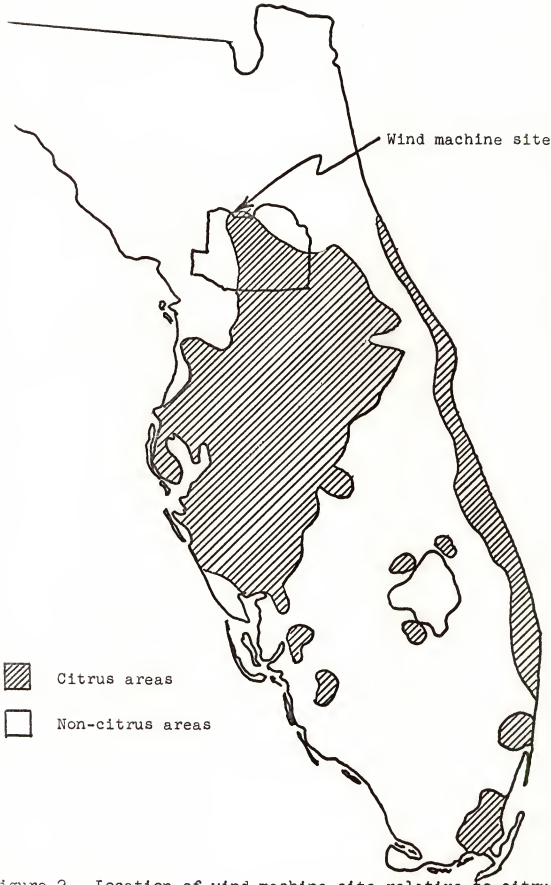



Figure 2. Location of wind machine site relative to citrus areas.

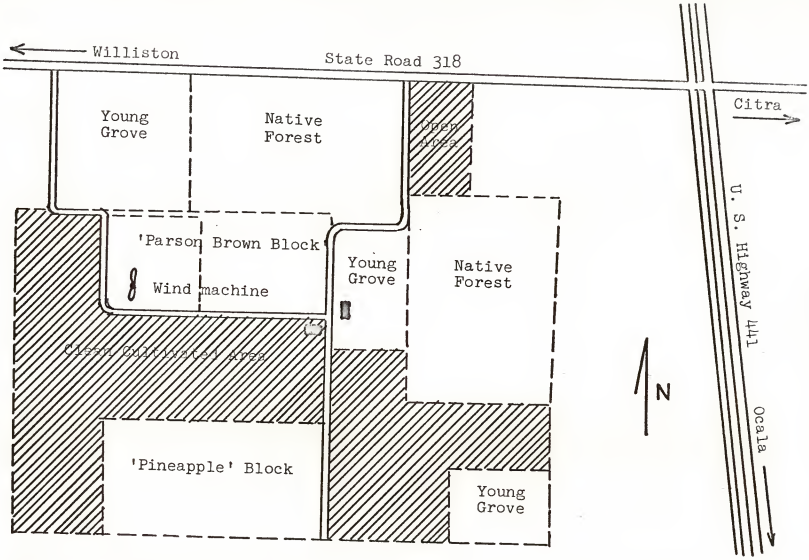



Figure 3. Diagram of area immediately around the W. R. Brown, Jr. citrus grove.

block used in this experiment, approximately 10 acres, was the west half of a 20-acre grove. The south and west margins of the grove faced cleared and cleanly cultivated land whereas the east and a portion of the north boundary faced on young citrus plantings as indicated in Fig. 3. The portion of the north boundary not bordering on the young citrus planting was bordered by a tall native forest cover.

## Wind Machine Description and Location

The wind machine was located in the previously described citrus grove approximately 250 feet from the south border and 250 feet from the west border. This location placed the machine 365 feet diagonally from the southwest corner of the grove (Fig. 4).

The wind machine used was a Tropic Breeze GP-332 equipped with a gasoline engine. The machine was a ground-powered model with a Ford V-8 industrial engine delivering 85 horsepower at the fan. The height of the wind machine tower was 31 feet 6 inches. The fan was 15 feet 4 inches in diameter and was constructed from ultra-strength aluminum alloy with an airfoil section 64-07 as registered with the National Advisory Committee of Aeronautics. It was equipped with a swivel-mounted hub to reduce the vibration and excessive strain on the tower and engine caused by gusts of wind on the fan blades. This fan was a standard production line model designed to turn at 590 rpm, and was built by the National Frost Protection Company.

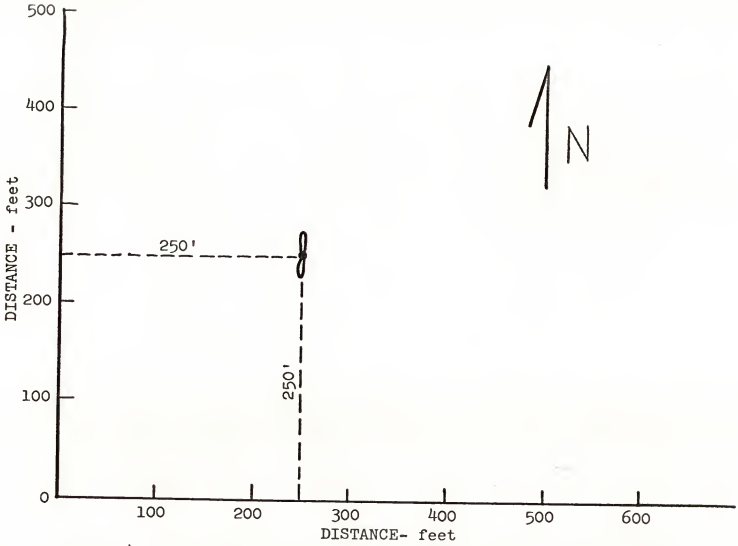



Figure 4. Wind machine location in 'Parson Brown' orange block.

The engine was equipped with a tachometer to give an accurate check on the rpm delivered by the power unit. The engine was operated at 2540 rpm during the entire test program.

## Instrument Trailer and Power Supply

A semi-trailer van was used as headquarters for the field operations and housed all of the recording instruments. The van was located between the west and northwest legs of the measuring network about 50 feet from the wind machine tower. The layout of the van interior is shown in Fig. 5.

Power was supplied for the operation of all instrumentation by a diesel generator which produced 110-115 volt, 60-cycle current. The power source was regulated by voltage and cycle meters to obtain a constant voltage at the proper number of cycles.

## Instrument Tower Layout

The same basic network was used throughout the entire project with improvements being made from time to time. The network (Fig. 6) consisted of 6 legs radiating out from the base of the wind machine tower to the southeast, south, southwest, west, northwest and northeast. The south and west legs only extended 200 feet from the wind machine base. The other legs extended 300 feet or more depending on the margins of the grove.

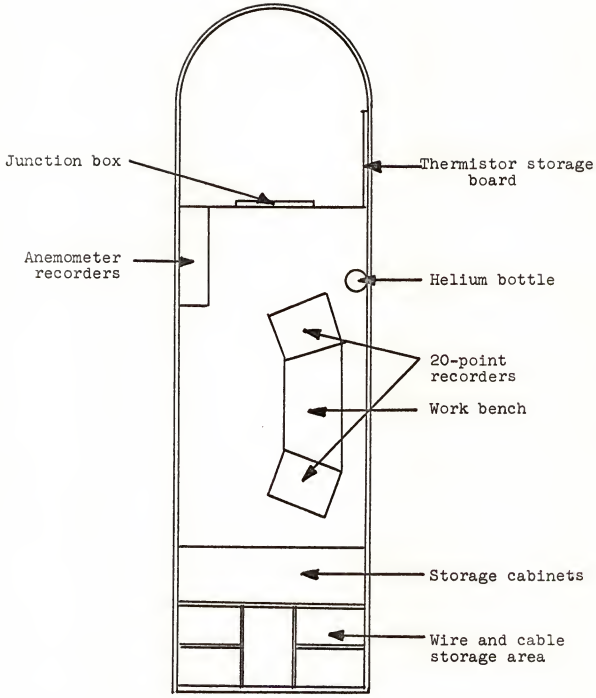



Figure 5. Interior of instrument van showing location of instruments and storage areas.

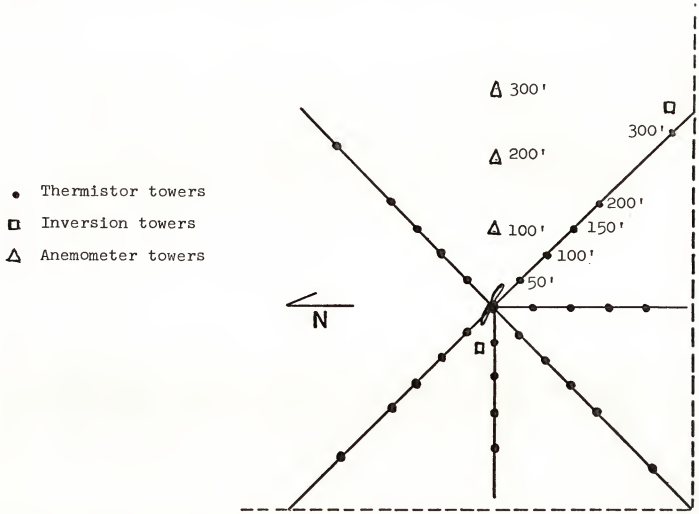



Figure 6. Instrumentation pattern in W. R. Brown, Jr. grove.

Temperature towers were placed every 50 feet for the first 200 feet. All towers beyond this point were spaced 100 feet apart.

Two inversion towers were used to measure temperatures up to 50 feet. One tower was located at the terminus of the southeast temperature leg or approximately 325 feet from the wind machine. The second inversion tower was located on top of the semi-trailer near the base of the wind machine.

The anemometer towers were located in a line east of the wind machine. The weather shelter was located 125 feet east of the wind machine.

## Instrumentation

Thermistors: General Electric thermistors, Type 2-D-102, were used as air temperature transducers during the 1961-62 research period. While these thermistors were good measuring devices, they proved impractical for this type of field operation because they varied immensely in their temperature-resistance curves. Due to this wide variation, the recorders available for this project could not be adjusted to handle all of the thermistor curves simultaneously. Some thermistors were always out of the range of the recorders, either off the high or low ends of the scale.

The complete thermistor network was rebuilt before the 1962-63 research period began; the General Electric thermistors were replaced with Yellow Springs Instrument Company thermistors, Type 44005. This group of thermistors had

matched temperature-resistance curves, giving a set of thermistors which could be used interchangeably with one another if failures developed in the system.

The resistance of the YSI 44005 thermistor was 3,000 ohms ± 1 percent at 25° C. Other specifications supplied by the manufacturer were: (1) a time constant of 10 seconds and (2) a dissipation constant of 1 milliwatt per degree centigrade. The coefficient of resistance was -4.94 percent per degree centigrade. Physical dimensions supplied by the manufacturer gave the diameter as 0.09 inches and the maximum thickness of the bead as 0.05 inches.

The thermistors were coated by the manufacturer with a covering of black epoxy resin. All soldering was carried out using a heat sink to avoid changing the thermistor resistance values.

Thermistor Mounting and Shielding: The thermistors were mounted and shielded in such a way as to get the maximum free air movement, to obtain shielding from nocturnal radiation and to secure easily interchangeable units. The mounting and shielding technique is shown in Fig. 7.

The thermistors were first soldered to 14-inch lengths of #22 plastic-coated wire and then placed in a protective fiberglas tubing except for 1/2 inch directly behind the thermistor head. The shielded wires were then placed inside a 12-inch length of 3/8-inch aluminum tubing. The thermistor was allowed to extend 1/2 inch out of the tubing and

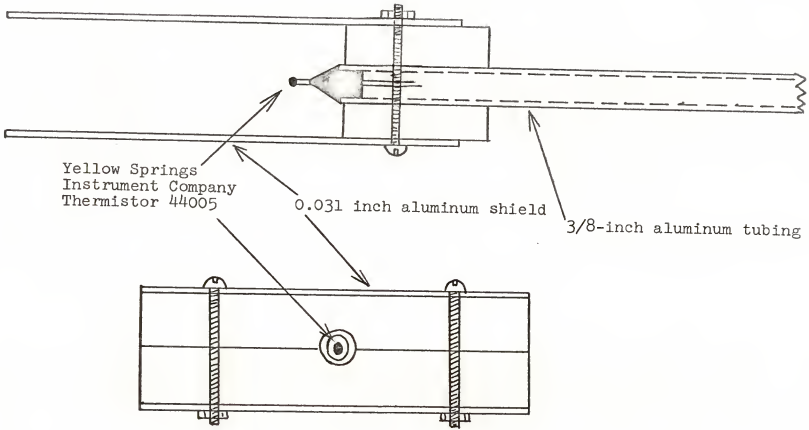



Figure 7. Mounting and shielding technique for YSI 44005 thermistors.

then was sealed in place with a synthetic rubber compound.

The protuding wires at the opposite end were soldered to a male Amphenol plug (AN-3106A-16S-5P) and connected to the aluminum tubing by a Cannon connector (K-06-16-3/8). The other half of the connection was made by an Amphenol female receptacle (AN-3102A-16S-5S). This was mounted on the thermistor tower (Fig. 8).

The thermistors were shielded from incoming and outgoing radiation by aluminum plates placed above and below them. The aluminum plates measured 4 by 5 inches and were 0.031 inches in thickness. Two blocks of hardwood measuring 4 inches by 3/4 inch by 1 inch were used as spacers to keep the shields away from the thermistor bead. The blocks were bored to fit snugly around the 3/8-inch tubing. Two bolts were used to fasten the complete unit together. The finished unit allowed 3/4-inch clearance above and below the thermistor bead for free air passage.

Temperature and Inversion Towers: The above described thermistor units were mounted on 2 types of measurement towers. One type was a 20-foot tube-type tower, hereafter called a temperature tower, consisting of 2 10-foot sections of 1-1/4-inch tubular aluminum. These towers were held erect by slipping them over a 5-foot section of galvanized pipe driven into the ground. No guy wires were required with this type installation.

The second type of tower, hereafter referred to as an inversion tower, was made from 4-inch aluminum pipe and

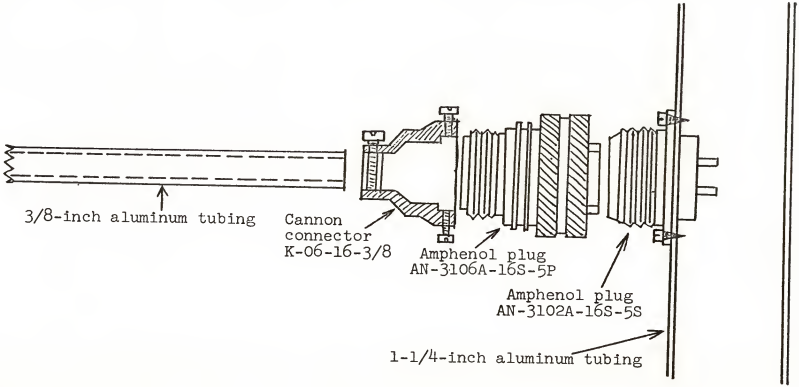



Figure 8. Diagram of connecting plugs and tower mounting bracket for shielded thermistor units.

reached to a height of 50 feet. The inversion tower was mounted on a hinged base and was supported in the upright position by guy wires at 20 and 40 feet.

Amphenol receptacles (AN-3102A-16S-5S) were mounted on the temperature and inversion towers at the 5 and 20-foot levels to accommodate thermistor units. In addition, the inversion towers had receptacles at 35 and 50 feet. Wiring from the thermistor receptacles connected with another receptacle at the base of the tower. All the above-ground wiring between the receptacles was located inside the hollow tubing. The temperature and inversion towers were connected to the recorders by multiwire cables.

Recorders: Instrumentation used to record the signals from the thermistors were Leeds and Northrup Company "Speedomax G, Model S" recorders equipped with 20-point switching units with multicolor inking pads. Three recorders with a total of 60 temperature points were used in this project. Each of the recorders had full-scale deflection of 20 millivolts.

In addition to the standard equipment, the 3 recorders were equipped with a thermistor bridge built especially to fit the requirements of the YSI type 44005 thermistor. The bridge was basically a Wheatstone type slightly modified to give the desired sensitivity with negligible self-heating of the thermistor. The bridge was inserted between the thermistor and the recorder input to develop a potential to drive the recorder. The bridge is shown in Fig. 9. Details of this bridge are described by Oswalt (65).

| | |
|---|---|
| 20 PR | 20-point recorder |
| E | 1.4 volt battery |
| R-1 | Fixed resistor, 2000 ohms |
| R-2 | Fixed resistor, 2800 ohms |
| R-3 | Coarse balance adjustment, 0 to 5000 ohms |
| R-4 | Fine balance adjustment, 0 to 100 ohms |
| R-5 | Current limiting resistor, 0 to 5000 ohms |
| R-6 | Sensitivity adjustment, 0 to 20 K |
| T | YSI 44005 thermistor |

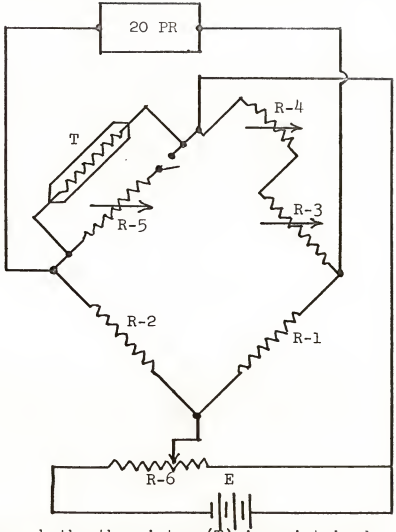



Figure 9. Thermistor bridge: Current through the thermistor (T) is maintained below selfheating point by adjusting current limiting resistor (R-5).

Anemometers: A total of 6 anemometers were used in this research and were mounted at heights of 5 and 20 feet above the ground surface. Three anemometer towers were used at distances of 100, 200 and 300 feet east of the wind machine tower. The anemometers were Casella sensitive anemometers manufactured in England. The instruments were sensitive between 25 feet per minute and 5,000 feet per minute. The revolutions per minute were recorded at a distance with electromagnetic counters. The contact assembly of the anemometer was geared to close twice for every 3 revolutions of the cups. The signals were carried on solid telephone wire to the counters.

A constant voltage supply was built to produce a regulated 6-volt direct current for the system.

Radiometers: Two Beckman and Whitley thermal radiometers were mounted on tripod base towers approximately 100 feet east of the wind machine base. One was a model H-188 hemispherical radiometer; the other was a model N-188 net radiometer. The radiometers were equipped with a sensing element composed of silver-constantan thermopiles arranged in a thin phenolic plate.

Air was blown across the phenolic plate to eliminate the convective influences and to keep the plate free of all forms of moisture. The radiometers were maintained at a height of 15 feet and kept leveled.

Soil Heat Flow Plates: The soil heat flux was measured using 3 Beckman and Whitley model ST 201-1 heat flow transducers. These transducers consisted of many closely concentrated thermocouple junctions of silver-constantan in a thin phenolic plate. These plates measured the heat flow gradient in the soil and were placed at a depth of 1/2 inch below the soil surface.

Outputs from the radiometers and the soil heat flow plates were recorded on a Leeds and Northrup Company "Speedomax G" 20-point recorder with a 20-millivolt full-scale deflection.

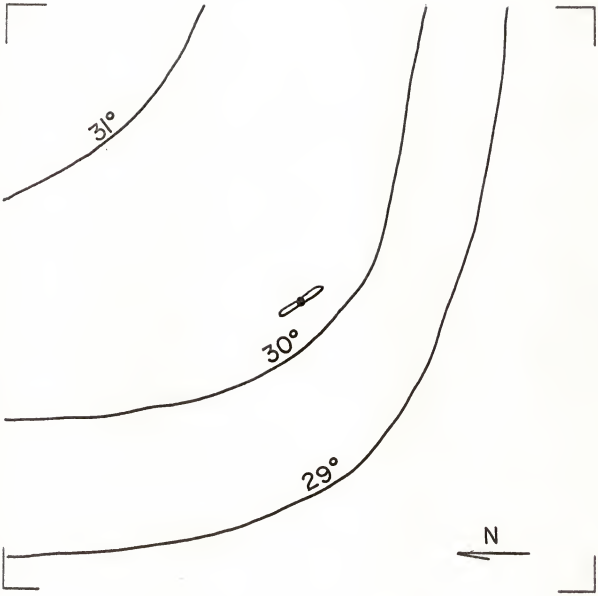
Other Instrumentation: Two calibrated hygrothermographs were located in 2 areas in standard United States Weather Bureau instrument shelters along with minimum thermometers. One shelter was located 125 feet east of the wind machine base. The other one was located 1/4 mile south of the machine on a site of comparable elevation, among trees of a similar age.

## RESULTS AND DISCUSSION

### Plot Characteristics

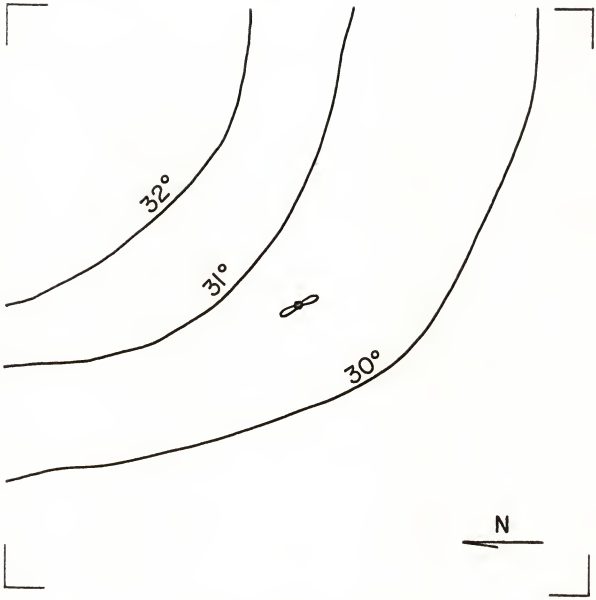
The area used for this research was not as level and uniform as might be desired for evaluation of research involving measurement of temperature differences as a guide to cold protection, but it was typical of an average grove in the ridge area of Florida. The northeast corner was the point of highest elevation whereas the south and west margins were the lowest areas. Isotherms at the 5-foot level when the machine was not in operation show a differential of approximately $2^{\circ}$ F from the highest point to the lowest (Figs. 10 and 11). Figs. 12 and 13 show isotherms taken at the 20-foot level when the machine was not in operations. Fig. 11 was recorded at the same time as Fig. 12. It can be noted that the differential at this particular time was $4^{\circ}$ F at 20 feet as opposed to $2^{\circ}$ F at 5 feet. Fig. 13 shows a $2^{\circ}$ F variation on another night at the 20-foot level. At the same time, at the 5-foot level (Fig. 14), only a $1^{\circ}$ F difference can be observed. In both instances the 20-foot level has twice the temperature differential as is shown at the 5-foot level.

The test area also had many replanted trees which caused some lack of uniformity of tree height. The replants are shown in Fig. 15. It can be noted that the southwest



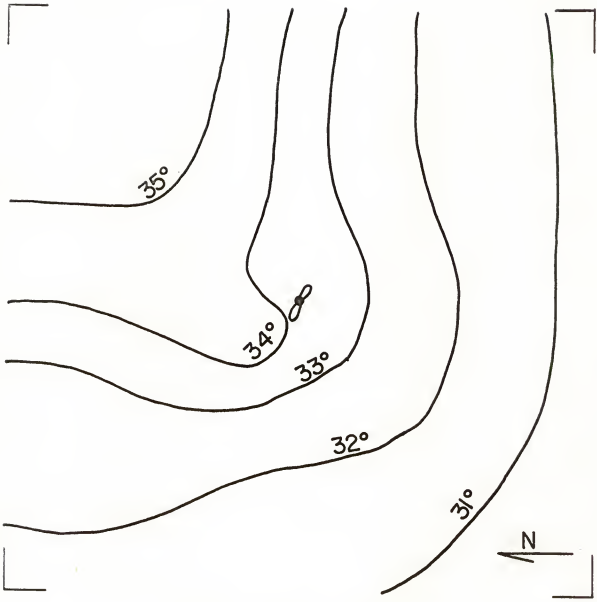

Date: December 13, 1962
Time: 5:40 PM
Level: 5 foot
Wind: NNW, 0-1 mph

Figure 10. Isotherms over the 8.25-acre test area before the wind machine was started.



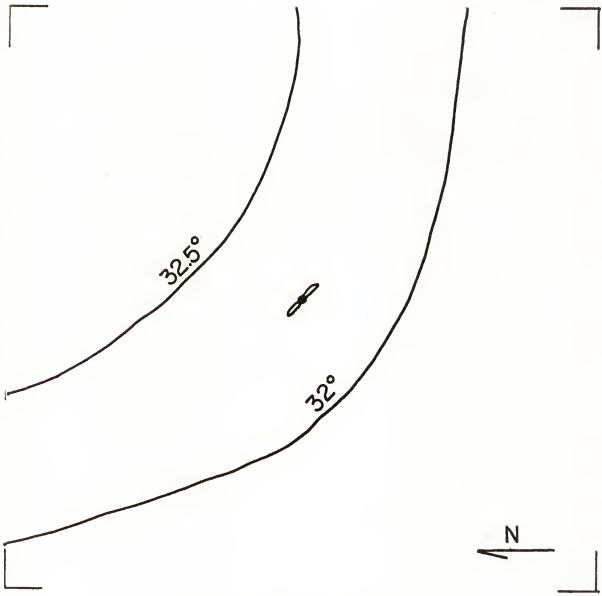

Date: January 4, 1963
Time: 2:20 AM
Level: 5 foot
Wind: NNW, 0-1 mph

Figure 11. Isotherms over the 8.25-acre test area before the wind machine was started.



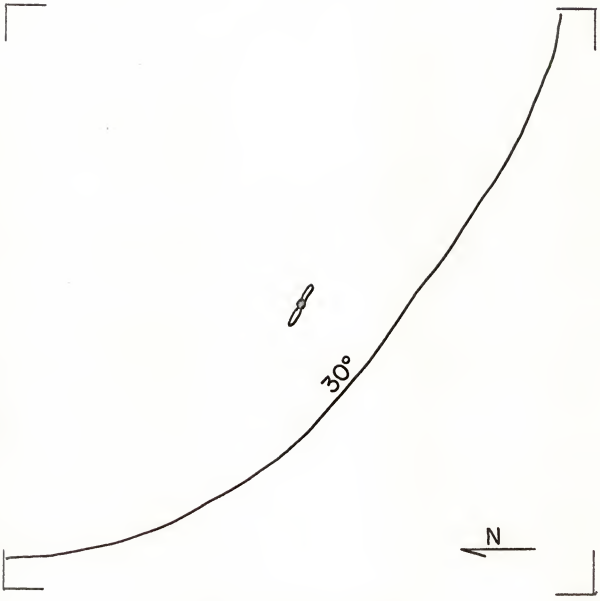

Date: January 4, 1963
Time: 2:20 AM
Level: 20 foot
Wind: NNW, 1-2 mph

Figure 12. Isotherms over the 8.25-acre test area before the wind machine was started.




Date: January 8, 1963
Time: 2:40 AM
Level: 20 foot
Wind: Calm

Figure 13. Isotherms over the 8.25-acre test area before the wind machine was started.




Date: January 8, 1963
Time: 2:40 AM
Level: 5 foot
Wind: Calm

Figure 14. Isotherms over the 8.25-acre test area before the wind machine was started.

Legend for Figure 15

O = Healthy full-size tree

R = Young replanted tree

X = Missing tree

```
R O O O O O O O O O O O O O O O O O O O O O R O X  25
O O O O O O O O O O O O O O O O O O O O O O O X R  24
O O O O O O O O O O O O O O O O O O O O O O O R R  23
R R O O O O O O O O O O O O R O O O O O O O O R R  22
O O O O R O O O O O O O O O O O R O O O O O R R   21
O R O O O O O O O O O O O O O O O O O O O O O R   20
R R O O O O O O O O O O R O O O O O O O O O O O   19
O O O O O O O O O O O R O O O O O O O O O O O O   18
O R O O O O O O O R O O O R O O O O O O R O O O   17
R O O O O R R O O O R O O R R O O O O O O O R O R 16
O O O O O O O O O O O O R O O O O O O O R O O R  15
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O O R R O O R O O O O O O O O R R O O O R O O R O X 13
O O R O O O O O R O O O O O O R O O O O O R O R O X 12
R O R R O O O O R R O O O O O R O R R O O O O O X X 11
R O O R R O O O O R R O O O O O O X R O O R O O X X 10
R R O R R O O O R R O O O O O O O O R O O O R X X X  9
O O O R O R O O O R X O O O O R O O O O X O X X X X  8
O R O O O O O R O O R O O O O O O O O X O X X X X X  7
O O O O O O O O O R R O O O R O X O R X X X X X X X  6
R O O O O O O O O O R O R O R R O O X X X X X X X X  5
R R R O O O R O R R O R R O R O R X X X X X X X X X  4
R O R O O R O R O R O R O O O O R X X X X X X X X X  3
X R O O O O O O R R O R R O R O O X X X X X X X X X  2
R O R R R R O O R R R R O R O X X X X X X X X X X X  1
                                                      N
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
```

Figure 15. Plat of W. R. Brown, Jr. grove

corner had numerous missing trees due to previous cold intrusions before the wind machine was placed in the grove.

Due to the area covered and the limitations in equipment, budget and time, this experiment was not replicated. Rather than comparing replicates, the same area was studied on several nights.

The plot area was fairly well isolated from the main heated area around McIntosh, Florida, but 1 small heated area lay north of the research site. The heaters in this area were usually not operated until the temperature reached 24 to 26° F. Also, the natural northwest drift carried most of the heat to the east of the test block. Little heating influence could be noted on most nights.

During the winter months, the Brown grove was kept cleanly cultivated by use of a disk harrow and was generally uniform throughout.

The irregularity in the tree height due to the replants may have influenced temperature readings at certain towers when the jet and associated eddy currents moved across the thermistors. All of the thermistors except 2 were placed between 4 mature trees. The 2 thermistors not between 4 mature trees had 3 mature trees with either a replant or an open area on 1 side.

Some influence could be noted in the northeast quadrant as the cooler air from the higher elevations tended to distort the isotherm pattern on occasions. This distortion had little or no influence on the operation of the wind

machine since the air moving down the hillside was usually in the same temperature range as the wind machine jet pushing outward.

## Instrumentation Problems

Due to the failure of the thermistor network during the 1961-62 season, only the hygrothermographs and minimum thermometers gave reliable data. Although some important information was gained during the 1961-62 season, the most valuable portion of the whole operation was the experience gained in handling the thermistor network. The wind machine was operated on 4 nights in December, 1961 and January, 1962.

Temperatures shown in Figs. 16 through 19 were taken on calibrated hygrothermographs in standard instrument shelters. The test station temperatures were read 125 feet east of the wind machine base whereas the check temperatures were read 450 feet east of the wind machine base. Figs. 16, 17, 18 and 19 show the temperature differences that existed on nights of the test runs.

On December 24-25, 1961, the drift was variable from the WNW to NW at speeds from 1 to 4 mph (Fig. 16). No inversion temperatures could be taken due to the network failure. Shortly before 6:00 AM on the morning of the 25th, a cloud cover moved over the area causing a sharp rise in the temperature.

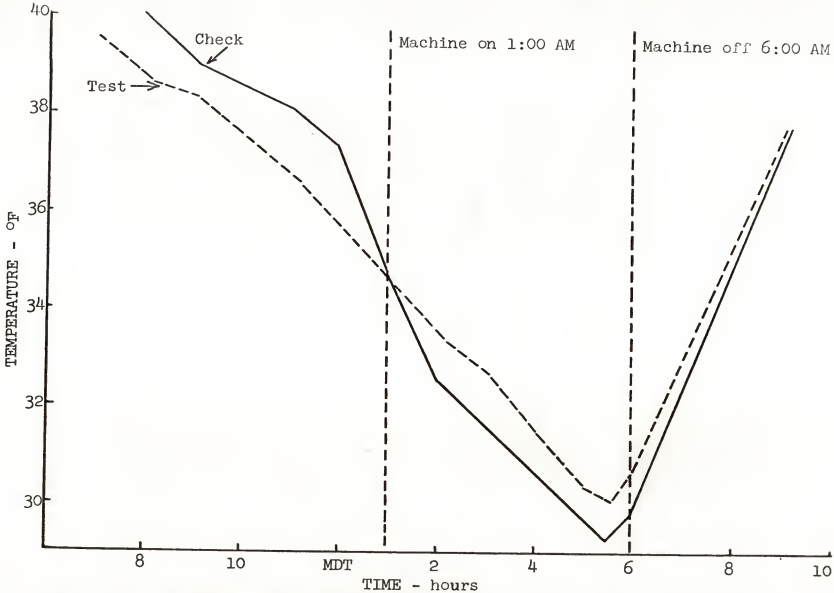



Figure 16. Hygrothermograph record for December 24-25, 1961, showing the temperature modification by the wind machine.

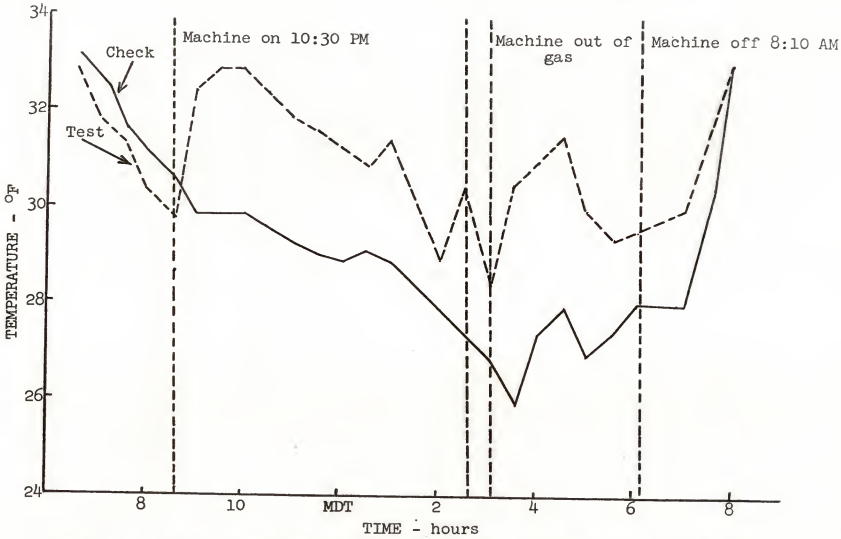



Figure 17. Hygrothermograph record for December 25-26, 1961, showing the temperature modification by the wind machine.

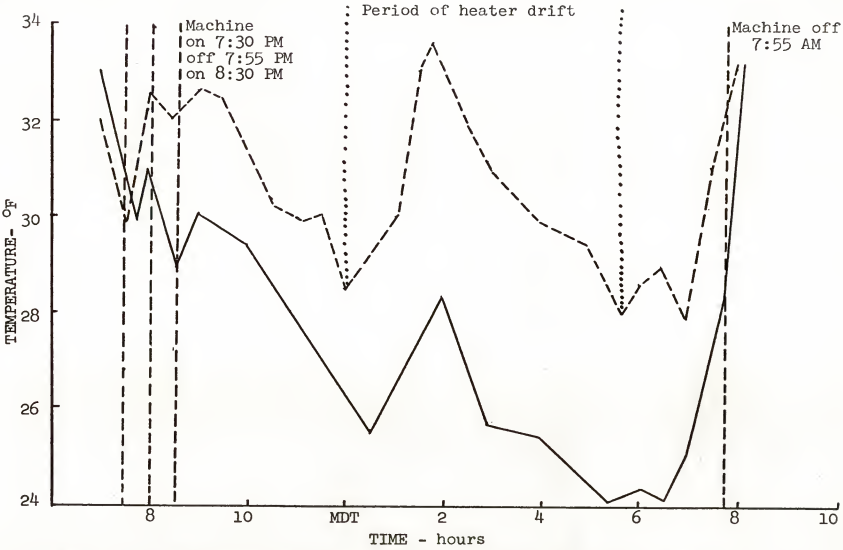



Figure 18. Hygrothermograph record for December 29-30, 1961, showing the temperature modification by the wind machine.

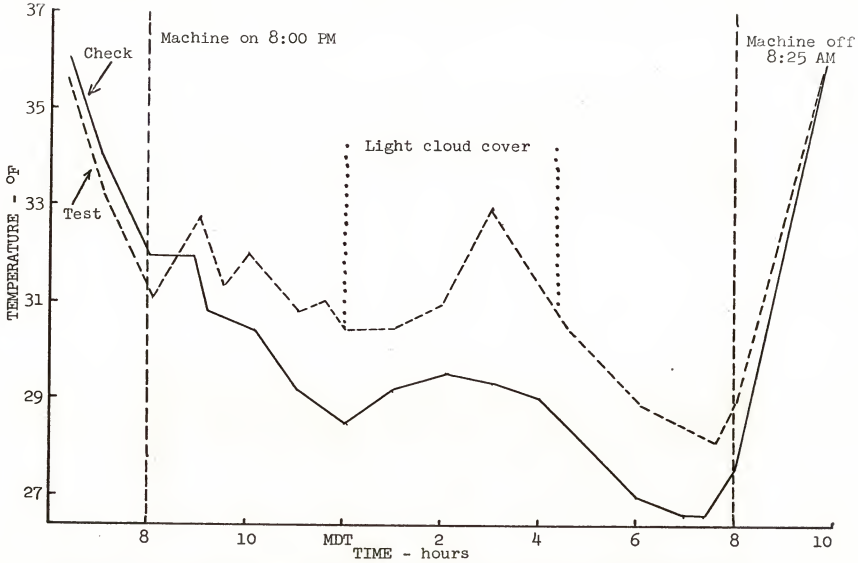



Figure 19. Hygrothermograph record for January 12-13, 1962, showing the temperature modification by the wind machine.

The night of December 25-26, 1961 (Fig. 17), was a clear, calm, radiation night with hardly any noticeable drift. There were periods of light drift, northerly at 0 to 1 mph, and there were periods of calm. Freezing temperatures were recorded at approximately 9:30 PM, and the wind machine was started at 10:30 PM when the temperature reached 30° F. An immediate temperature rise was noted soon after the wind machine was started. This rise was approximately 3.2° F, and 2 hours later, it was still 2° F above the check thermometer. The heaters in the neighboring grove to the north were lit at 1:45 AM, and shortly thereafter, some increase in both the test and check thermometers was noted. At 4:35 AM the wind machine ran out of gasoline and could not be started again until 5:10 AM. During this period, a 2° F loss in temperature was noted. When the wind machine was started again, the loss was immediately regained, and even some additional rise was noted. At this time, a 3.5° F difference could be measured between the test and check stations. The minimum at the test station was 28.5° F whereas the check station recorded 26.0° F. Temperatures 1/4 mile north of the wind machine were recorded as low as 24.0° F when the heaters were lit. This indicated that the wind machine may have been giving some protection at the check station.

The night of December 29-30, 1961 (Fig. 18), was clear with a NW drift varying from 0 to 1 mph. The wind machine was started at 7:30 PM and gave temperature increases both

at the test station and the check station. The wind machine was stopped at 7:55 PM to determine if the rise was solely due to the machine or if possibly the change was meteorological. The temperatures fell rapidly, and the machine was started again at 8:30 PM. Again there was a good response. The average temperature rise was 2.5° F in the first hour after the machine was restarted.

Heaters were lit in the adjoining grove at 10:30 PM and appeared to influence the test grove temperatures about midnight. Maximum benefit with the wind machine was noted between 2:00 AM and 6:30 AM when as much as a 4.5° F increase was noted.

The influence of cloud covers can be pointed out quite vividly in Fig. 19, January 12-13, 1962. Three visible cloud formations at 9:05 PM, 10:00 PM and from midnight to approximately 5:10 AM gave increases in the ambient air temperature. There was a very slight NW drift from 0 to 1 mph most of the night with some periods of calm. The wind machine caused an approximate 2° F rise at the test station above the temperature recorded at the check station. Minimum temperature at the check station was 25.6° F whereas the test station minimum was 27.2° F.

## Effectiveness of Wind Machine Protection

Protection and Inversion Data: The wind machine was operated on several nights during the 1962-63 season, and selected data were taken from these nights. This information

is shown in Table 1. The data shown gives a good cross section of the area of protection at various inversion strengths. Very little or no protection could be observed when the inversion strength was less than $1^{\circ}$ F. When the inversion strength became greater than $3^{\circ}$ F, the area of protection increased quite rapidly; and the area of protection at the $1^{\circ}$ F level was approximately 10 acres when an $8^{\circ}$ F inversion occurred.

The area of protection at the $4^{\circ}$ level was never very large even with inversions of $9.0^{\circ}$ F. Only a little more than 1 acre of $4^{\circ}$ F protection was observed with an 8 or $9^{\circ}$ F inversion. Two factors may come into play to keep this high temperature area reduced in size even though the inversion may be strong. The buoyancy of this warm air may cause it to rise rapidly and not give penetration for any distance. This factor coupled with the force of the cooler air pushing in on the outside of the area under the influence of the wind machine may reduce the area of protection.

From vertical and horizontal isotherms, the action of the wind machine can be visualized. When the wind machine is first started, the fan pushes air downward and away from the wind machine tower. This air is drawn into the fan mainly from elevations at or above the height of the fan and is then pushed away from the fan in the form of a jet cone. At the same time that it moves downward and outward, the jet is bent back due to the resistance of the more dense air and the trees in its path. The cool air is piled up in front

Table 1

Selected values showing the effectiveness of the wind machine at various inversion strengths and wind speeds

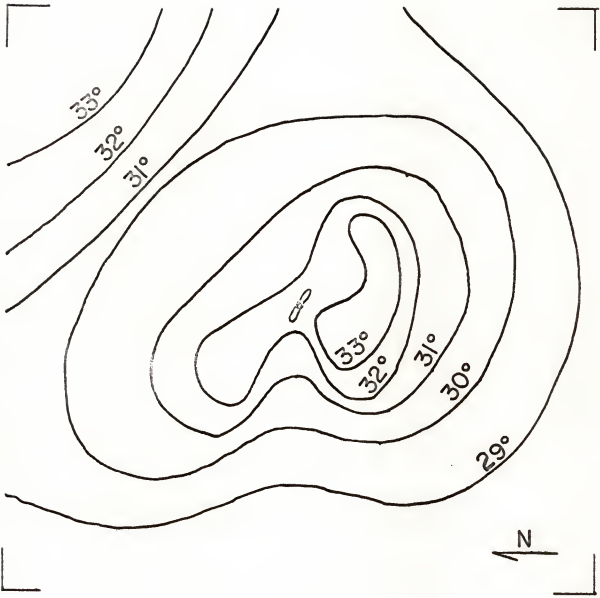
| Area of protection at 5-foot level (acres) | | | | Wind speed (mph) | | 5 to 50 feet inversion strength (°F) | Check temperature (°F) | Time and date | |
|---|---|---|---|---|---|---|---|---|---|
| 1° | 2° | 3° | 4° | 5 feet | 20 feet | | | | |
| 0.00 | 0.00 | 0.00 | 0.00 | 2.2 | 3.8 | 0.6 | 23.0 | 12:55 AM | 12/14/62 |
| 1.26 | 0.00 | 0.00 | 0.00 | 0.8 | 2.2 | 1.5 | 27.0 | 12:24 AM | 1/25/63 |
| 1.71 | 0.16 | 0.00 | 0.00 | 0.7 | 2.6 | 1.9 | 33.0 | 3:26 AM | 1/22/63 |
| 1.54 | 0.14 | 0.00 | 0.00 | 0.6 | 2.0 | 2.0 | 29.0 | 11:57 PM | 1/24/63 |
| 1.89 | 0.12 | 0.00 | 0.00 | 1.2 | 2.8 | 2.2 | 27.0 | 7:10 PM | 12/13/62 |
| 1.83 | 0.91 | 0.00 | 0.00 | 0.9 | 2.0 | 3.0 | 25.0 | 9:05 PM | 12/13/62 |
| 4.35 | 2.32 | 0.77 | 0.14 | 0.5 | 2.2 | 4.2 | 29.0 | 4:16 AM | 1/8/63 |
| 6.08 | 4.12 | 2.04 | 0.23 | 0.2 | 1.7 | 4.7 | 30.0 | 2:54 AM | 1/22/63 |
| 6.56 | 3.46 | 1.43 | 0.32 | 0.8 | 1.7 | 5.5 | 27.0 | 1:24 AM | 12/11/82 |
| 7.30 | 3.76 | 1.57 | 0.49 | 0.0 | 1.6 | 5.9 | 31.0 | 4:35 AM | 1/4/63 |
| 9.37 | 5.68 | 2.34 | 1.23 | 0.0 | 1.5 | 7.9 | 29.0 | 6:15 AM | 1/4/63 |
| 11.17 | 7.78 | 3.30 | 1.18 | 0.0 | 1.2 | 9.0 | 31.0 | 3:55 AM | 1/4/63 |

of the jet cone as it moves away from the wind machine. Part of this cooler air is entrained into the jet cone as it expands. The cooler, dense air continues to push back on the outside of the expanding jet until the jet weakens. As the force in the expanding jet weakens, the cooler air begins to move back in toward the wind machine base. Usually this intrusion is accomplished by air moving in close to the ground where radiation cooling is taking place. About the time this movement mounts momentum, the machine has started its next cycle and pushes against the cold air intrusion and rolls it back.

The wind machine in a sense pushes out a hole in the atmosphere, holding back the cold, dense air and at the same time adds heat to the system from air layers above tree height.

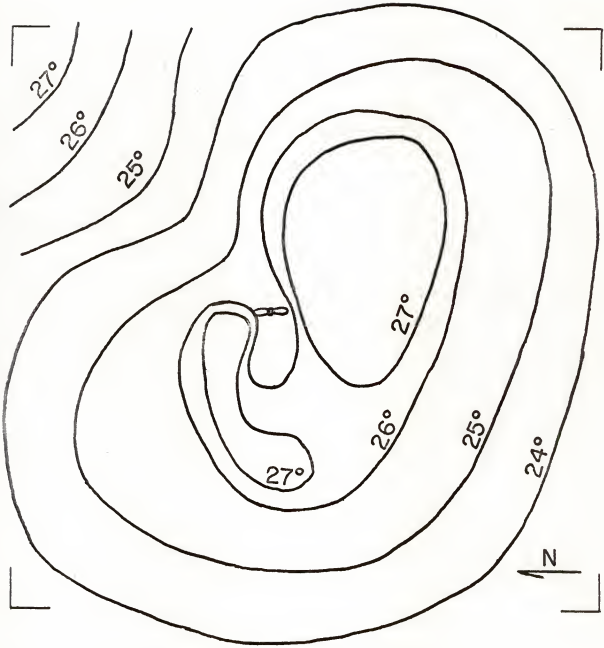
Typical Protection Isotherms: Observations using minimum thermometers and other temperature sensors with slow response times have shown circular or oval isotherm patterns. Using fast response thermistors and the capability of measuring the total area of the test in 80 seconds, the isotherms in many instances took on a different appearance. Rather than being round or oval, they often appeared to be kidney-shaped. The protection pattern of the wind machine was not static but was constantly changing, using the wind machine tower as a pivot point.

Figs. 20 through 27 show typical isotherm patterns as they occurred at the 5-foot level in a citrus grove.



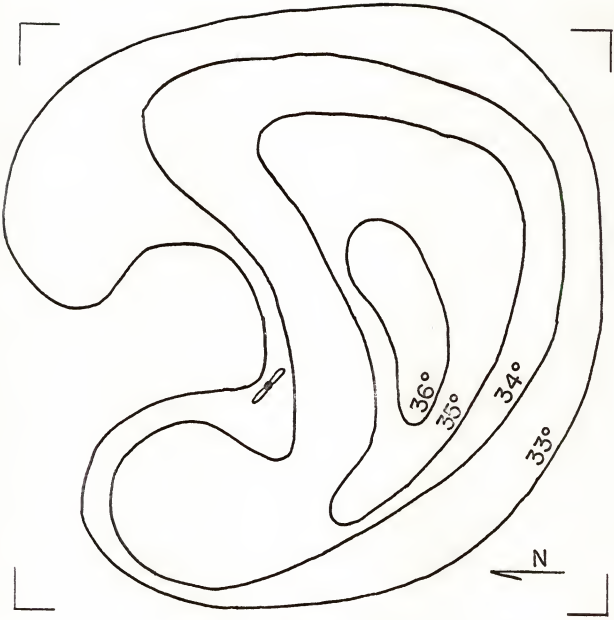

Date: December 10, 1962
Time: 10:44 PM
Level: 5 foot
Wind: WSW, 0-1 mph

Figure 20. Isotherms over the 8.25-acre test area produced by the wind machine.



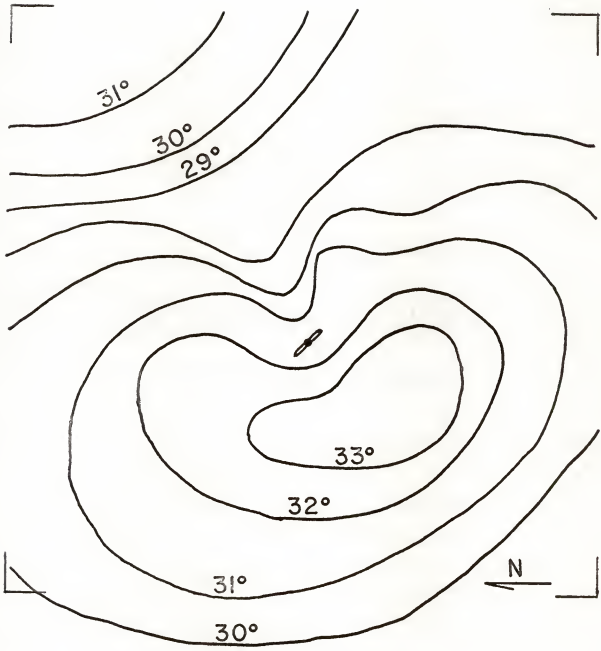

Date: December 13, 1962
Time: 9:05 PM
Level: 5 foot
Wind: NNW, 0-1 mph

Figure 21. Isotherms over the 8.25-acre test area produced by the wind machine.



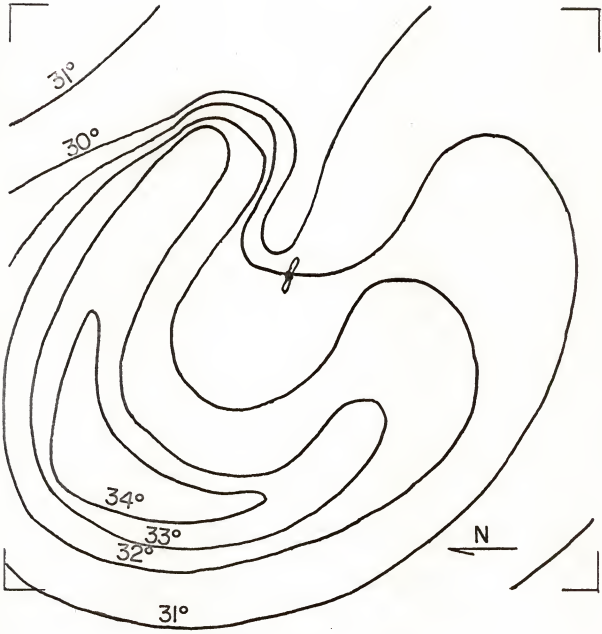

Date: January 4, 1963
Time: 3:20 AM
Level: 5 foot
Wind: Calm

Figure 22. Isotherms over the 8.25-acre test area produced by the wind machine.



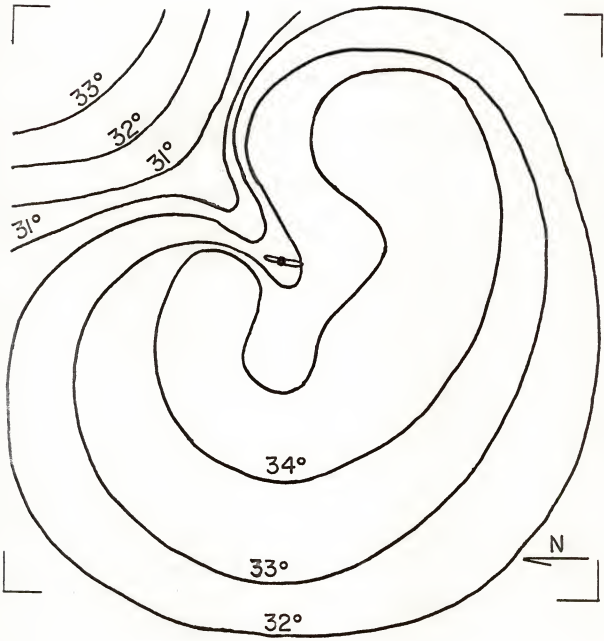

Date: January 8, 1963
Time: 6:18 AM
Level: 5 foot
Wind: Calm

Figure 23. Isotherms over the 8.25-acre test area produced by the wind machine.



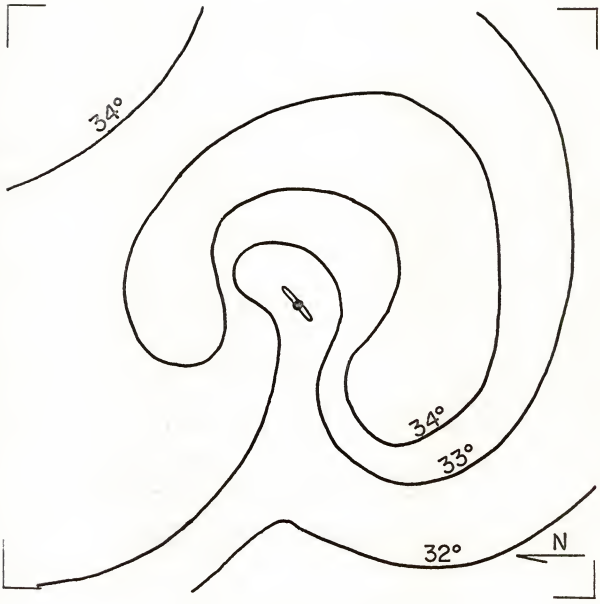

Date: January 22, 1963
Time: 2:06 AM
Level: 5 foot
Wind: Calm

Figure 24. Isotherms over the 8.25-acre test area produced by the wind machine.



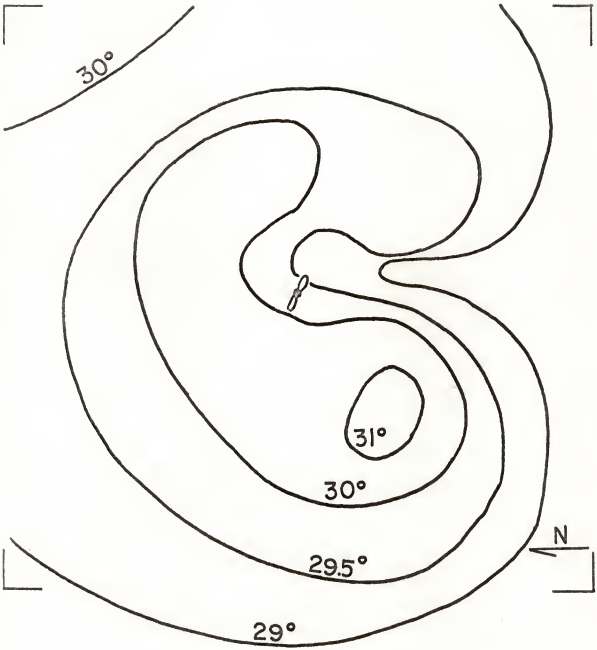

Date: January 22, 1963
Time: 3:00 AM
Level: 5 foot
Wind: Calm

Figure 25. Isotherms over the 8.25-acre test area produced by the wind machine.




Date: January 22, 1963
Time: 3:21 AM
Level: 5 foot
Wind: NNW, 0-1 mph

Figure 26. Isotherms over the 8.25-acre test area produced by the wind machine.




Date: January 24, 1963
Time: 11:57 PM
Level: 5 foot
Wind: WNW, 0-1 mph

Figure 27. Isotherms over the 8.25-acre test area produced by the wind machine.

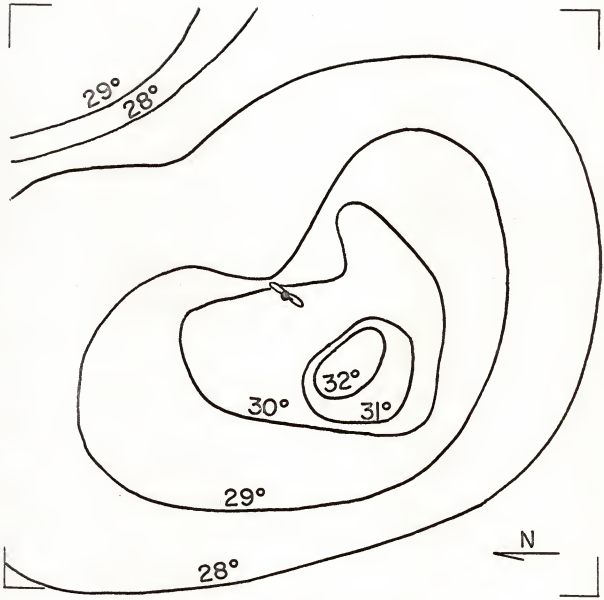
Figs. 20 and 21 were observed before the leaves dropped from the trees, whereas Figs. 22 through 27 were taken from data after the leaves had fallen from the trees. In every one of the isotherm diagrams, a depression can be observed on one side of the isotherms.

By making visual observations and by studying the turning jet, it was discovered that the depression occurred immediately in advance of the jet.

The same pattern was found to occur at the 20-foot level, but the inflow was not as brisk as at the 5-foot level. Figs. 28 and 29 show the 5- and 20-foot levels as they appeared on the morning of December 11, 1962, with leaves on the trees. Figs. 30 and 31 show the 5- and 20-foot levels in defoliated trees on January 8, 1963.

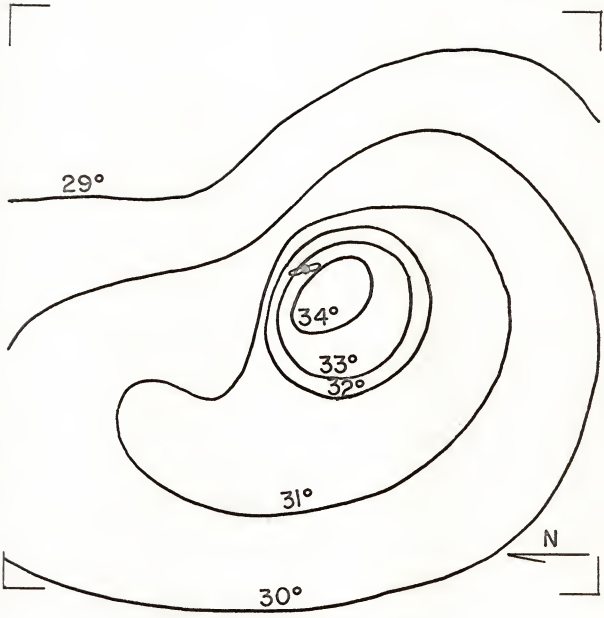
Comparing the isotherms of trees with leaves and without leaves, the isotherms do show some difference in appearance. The isotherms with leaves present were more oval or circular than those that occurred with the leaves missing. The kidney-shaped pattern was more pronounced without leaves but was still present even when the leaves were on the trees. The ease of air movement in bare trees was obviously greater because the trees offered less resistance than fully foliated trees with branches hanging near the ground. This would account for a more pronounced indentation when the leaves were not present.

Typical Flow Pattern: The flow of air around the wind machine was not all in an outward direction. By observing



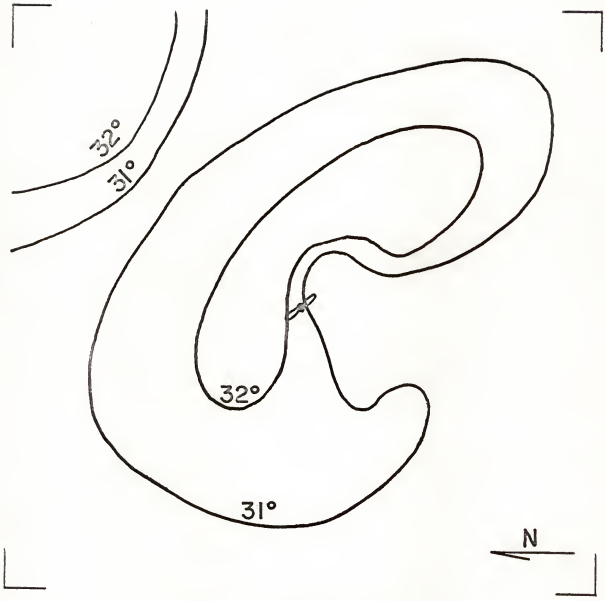

Date: December 11, 1962
Time: 2:49 AM
Level: 5 foot
Wind: WSW, 0-1 mph

Figure 28. Isotherms over the 8.25-acre test area produced by the wind machine.



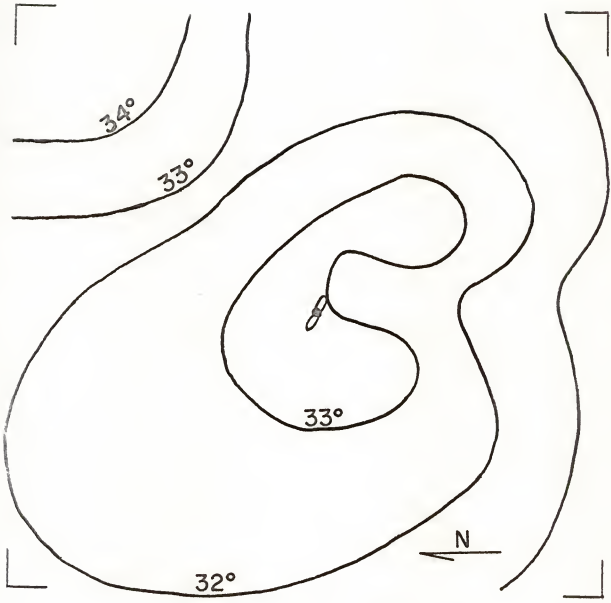

Date: December 11, 1962
Time: 2:49 AM
Level: 20 foot
Wind: WSW, 0-1 mph

Figure 29. Isotherms over the 8.25-acre test area produced by the wind machine.




Date: January 8, 1963
Time: 4:00 AM
Level: 5 foot
Wind: Calm

Figure 30. Isotherms over the 8.25-acre test area produced by the wind machine.




Date: January 8, 1963
Time: 4:00 AM
Level: 20 foot
Wind: Calm

Figure 31. Isotherms over the 8.25-acre test area produced by the wind machine.

a wind machine in operation in conjunction with lazy-flame heaters, flow patterns were demonstrated. There was an inward movement of air toward the wind machine base just prior to the passage of the turning jet (Fig. 32). This inward movement could easily be observed by watching the flame and smoke plumes of the heaters around the wind machine. The observations with the heaters substantiated the indented isotherm pattern recorded by the thermistor network. The pattern of air inflow was more pronounced on nights of relatively calm air than on windy nights. As the natural convection increased, the indentation decreased.

After the initial turning jet had passed approximately 90 to 120 degrees beyond a given point, a secondary area of mixing occurred. This eddy force apparently was able to carry on considerable mixing as it passed, because a rise in temperature could be recorded as the mixing occurred.

With this inward flow of air near the surface, the old theory of the wind machine drawing all of its air from heights at or above the blade seems to be in doubt. The machine apparently not only pulls air down from above but also pulls air up from lower elevations. Of course, all of the air moving in from below does not move the full distance to the fan to be mixed. Some of this cooler air is taken into the expanding jet as it progresses forward. This is shown in Fig. 32 by the arrows that curve into the expanding jet.

The area just in advance of the jet was the weakest

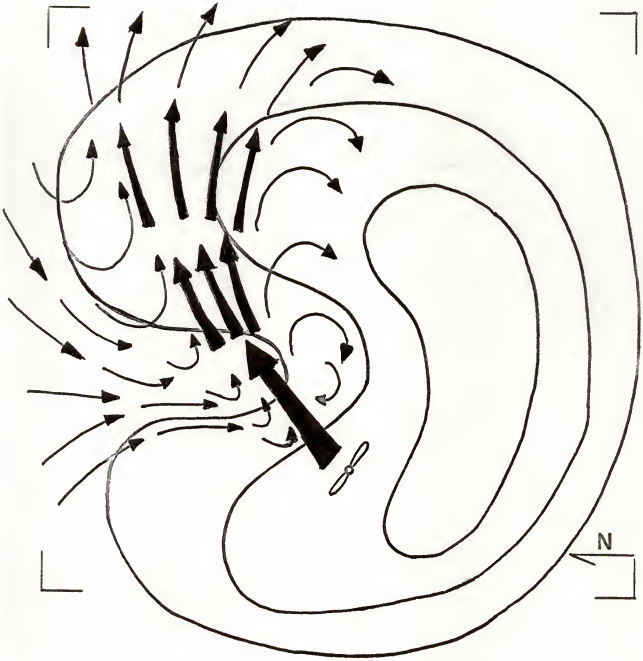



Figure 32. Typical air flow pattern showing the direction of air movement around the turning jet.

point in the hole pushed out by the wind machine. The pressure on the outer portion of this hole plus the suction type action of the fan set up a situation that favors this inward flow of cold air. The machine in a sense makes a low pressure area around itself as it pushes out a hole in the atmosphere.

Typical Cyclic Temperature Patterns: The wind machine did not produce isothermal condtions over a wide area. Neither did any point in this area remain at a constant temperature for any length of time. If several individual cycles of a wind machine are linked together from one reading point, a system not too different in appearance from saw teeth can be observed. Fig. 33 shows the pattern for simultaneous recordings at 5 and 20 feet at a distance 100 feet from the wind machine.

It should be noted that the thermistor at the 5-foot level did not necessarily follow the 20-foot level thermistor. In some instances, the 5-foot thermistor seemed to lag behind the 20-foot thermistor.

The mixing in the vertical profile was not complete or isothermal. The 20-foot level was always warmer than the 5-foot level even though frequent mixing was carried out.

Effect of Foliage on Cyclic Patterns: The pattern shown in Fig. 34 occurred with foliage present on the trees. Following the loss of foliage and fruit due to the freeze of December, 1962, a similar test was carried out on the same

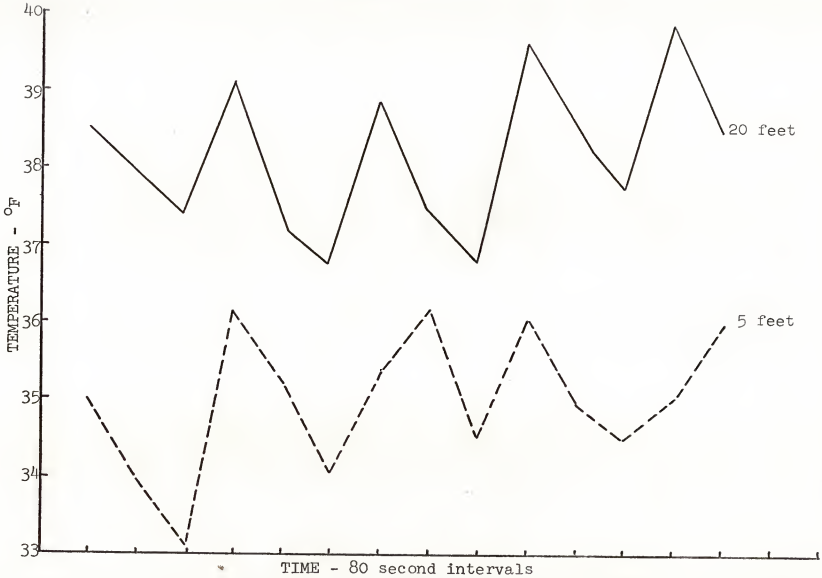



Figure 33. Typical repetitive temperature cycles at 5 and 20 foot elevations with the wind machine in operation.

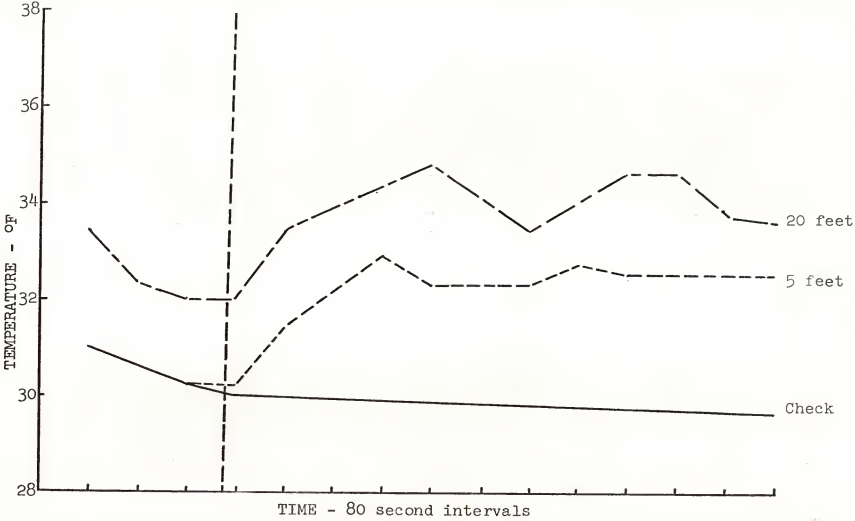



Figure 34. Repetitive temperature cycles following the start of the wind machine with trees with foliage.

set of thermistor points with the only difference being the lack of foliage and fruit. The grove following the freeze took on the appearance of a deciduous orchard rather than an evergreen citrus grove.

The temperature fluctuations at 5 and 20 feet (Fig. 35) without any foliage or fruit present were more pronounced and sharper than those found on the same trees with leaves present. The peaks and valleys appeared more like those present previously in the continuous cycles (Fig. 33).

The jet apparently was slowed down more when the foliage was present and created considerable eddy current action as it passed across the upper surface of the trees. Thus, the jet was modified to a greater extent than the jet passing over the bare branches of the deciduous type tree. As this mixing occurred over and around the foliated trees, the peaks and valleys (Fig. 35) were reduced or changed in form (Fig. 34).

Measurement of Single Cycles: On December 29, 1961, all 20 points on one Leeds and Northrup recorder were wired to record 1 thermistor continuously every 4 seconds. The time at which the wind machine was blowing directly on the thermistor was recorded each time it went through a cycle. The average time for a 360 degree rotation of the wind machine was 4 minutes and 23 seconds. The rotation time varied plus or minus 13 seconds.

Measurements were determined between 4:05 AM and 6:10 AM under clear, calm conditions with the wind drift

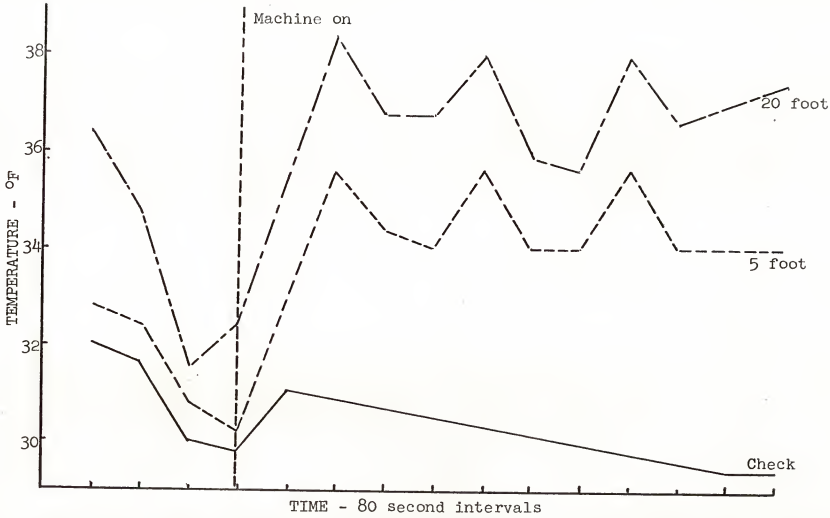



Figure 35. Repetitive temperature cycles following the start of the wind machine with trees without foliage.

less than 1 mph. The measurements were made at the 5-foot level at a distance of 100 feet from the machine in a southwesterly direction.

Many individual cycles were plotted, but no 2 cycles appeared identical during the 2-hour test period. Figs. 36, 37, 38, 39 and 40 are typical cyclic patterns where time was plotted against temperature. The first thing that became apparent was that the maximum temperature did not occur when the machine was blowing directly on the thermistor. The maximum temperature occurred approximately 90 to 150 degrees after the fan had passed the thermistor (Figs. 36, 37, 39 and 40). Fig. 38 does not show a real maximum peak but a series of peaks all about the same temperature.

Figs. 36, 37 and 39 show a small secondary peak prior to the main temperature peak which was probably due to eddy currents that were preceding the main turning jet. Figs. 36, 37, 38, 39 and 40 all show secondary eddy peaks following the main temperature peak.

The variation of time that it took the jet to make a 360-degree cycle probably could be traced to how much resistance the jet met with during its outward advance. The more the turning jet was bent, the longer it took for it to be measured at the same location again. If the resistance against the frontal edge of the cone was reduced, the jet appeared to move along more rapidly.

Observations of wind movements some 300 feet from the machine at the 5-foot level showed great variation in the

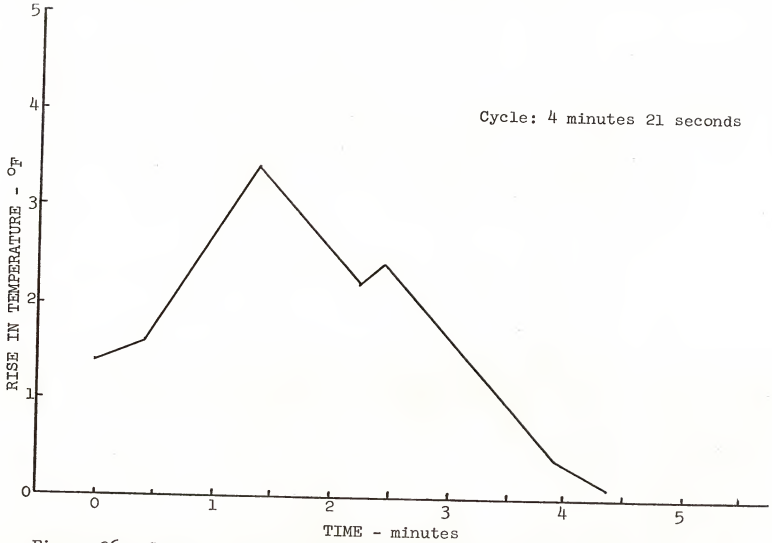



Figure 36. Single cycle of the wind machine 4:01 AM on December 29, 1961.

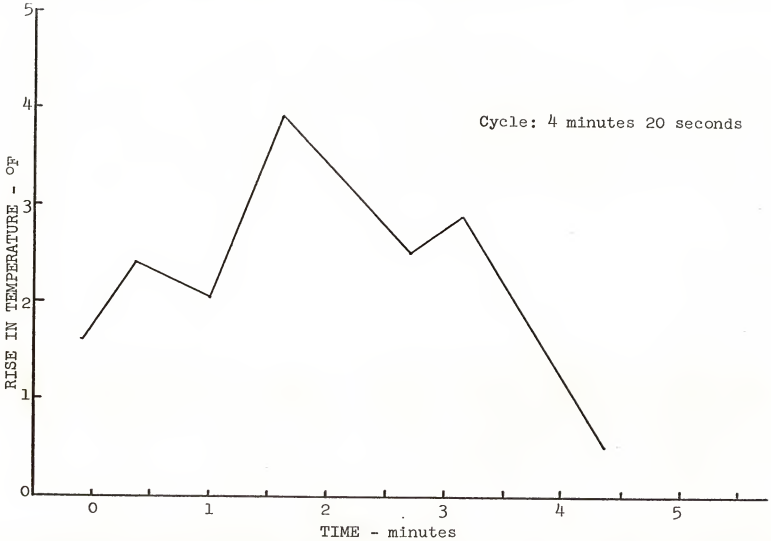



Figure 37. Single cycle of the wind machine 4:06 AM on December 29, 1961

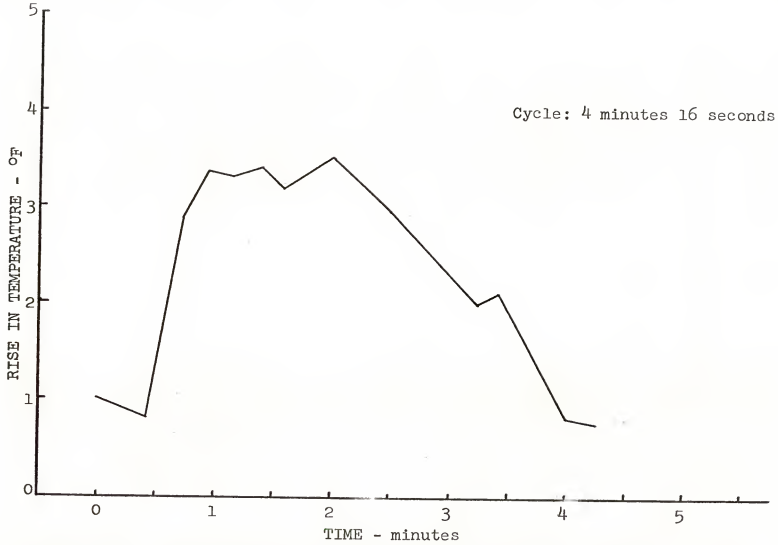



Figure 38. Single cycle of the wind machine 5:56 AM on December 29, 1961.

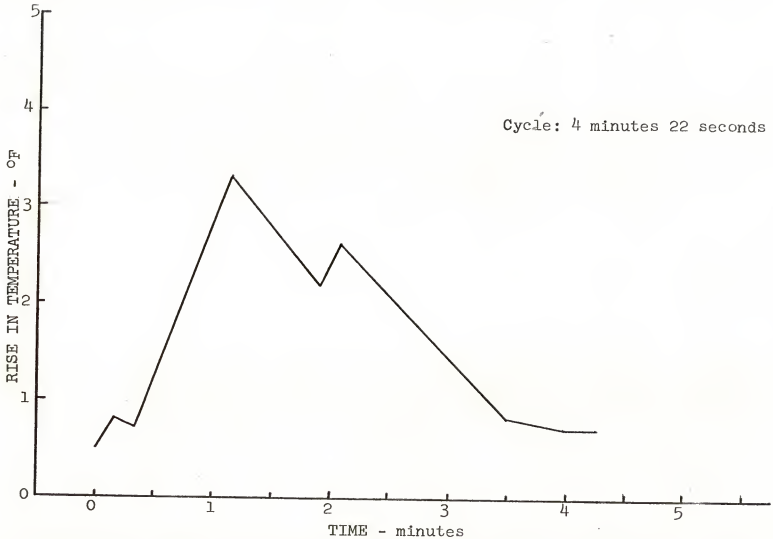



Figure 39. Single cycle of the wind machine 6:05 AM on December 29, 1961.

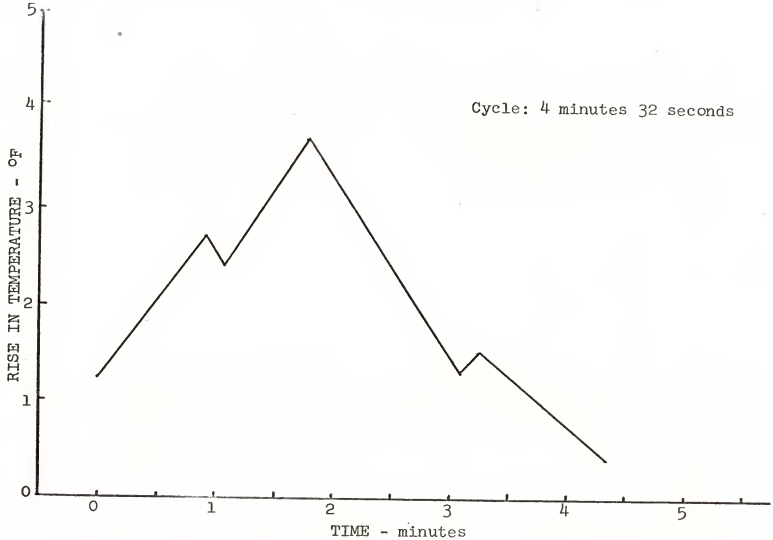
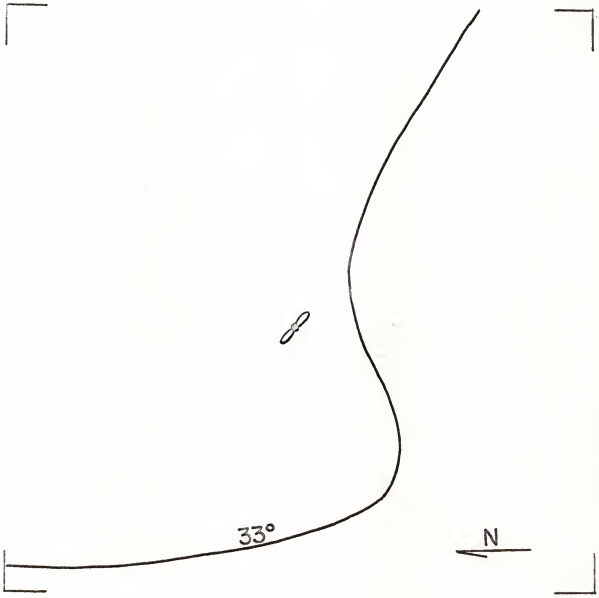



Figure 40. Single cycle of the wind machine 6:01 AM on December 29, 1961.

amount of the wind recorded each time the jet passed. On some occasions the jet appeared to miss the anemometer completely. Either the jet had been bent to such an extent that it passed inside the anemometer, or else it became buoyant and rose up over the test zone. Even the anemometer at 20 feet from the surface failed to record the passing of the jet.

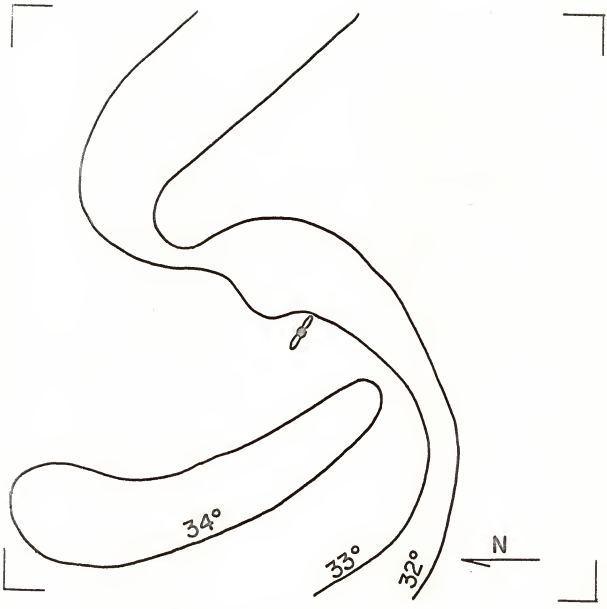
Patterns Following the Starting of a Wind Machine: The response times at 5 and 20 feet were markedly different. The first well-defined isotherms at the 20-foot level developed before those at the 5-foot level. Approximately 10 to 15 minutes after the machine was started, the 20-foot isotherms began to appear, whereas the 5-foot level did not develop isotherms for 30 to 35 minutes. This could very well be the reason researchers have reported a delayed response with the wind machine. They were probably measuring temperatures in weather shelters 5 feet above the ground. Actually the machine gave some protective action within 10 minutes of its initiation. The area of full protection ultimately reached by the wind machine probably took more than 30 minutes to develop. Figs. 41 through 50 show the various steps in the development of the protection pattern at the 20-foot level, whereas Figs. 46 through 50 show the 5-foot level development during the same time period.

The response times indicated in the previous paragraph were for trees with foliage present. These values were



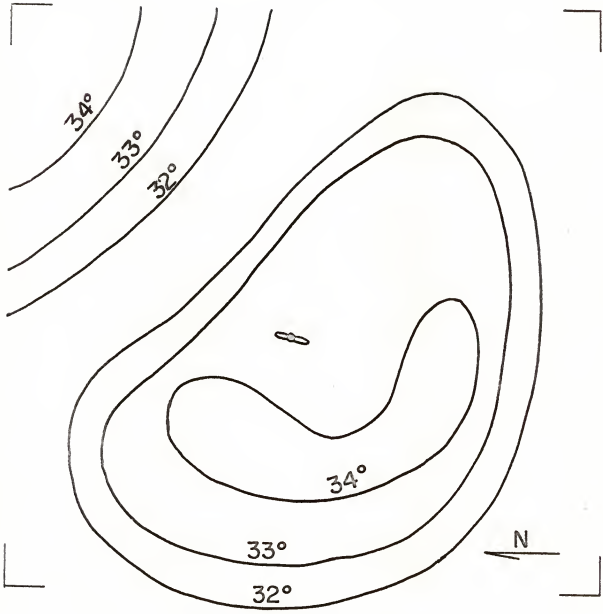

Date: December 10, 1962
Time: 9:50 PM
Level: 20 foot
Wind: Calm

Figure 41. Development of isotherm pattern following the start of the wind machine with foliage on the trees: Five minutes after the start of the wind machine.



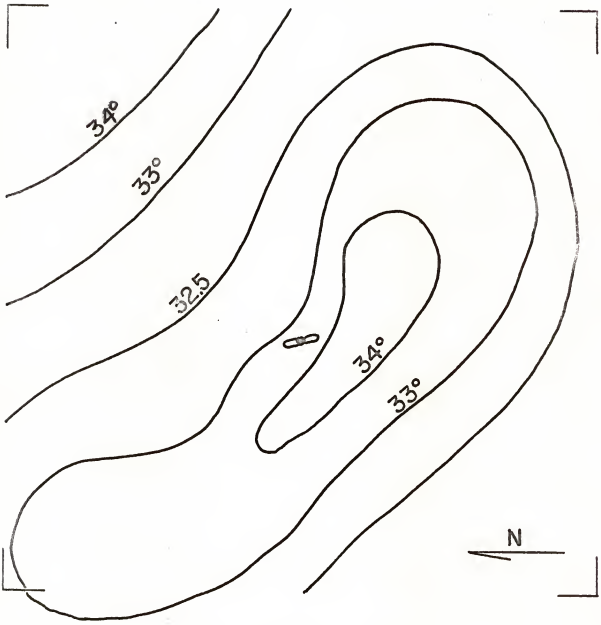

Date: December 10, 1962
Time: 9:56 PM
Level: 20 foot
Wind: Calm

Figure 42. Development of isotherm pattern following the start of the wind machine with foliage on the trees: Eleven minutes after the start of the wind machine.



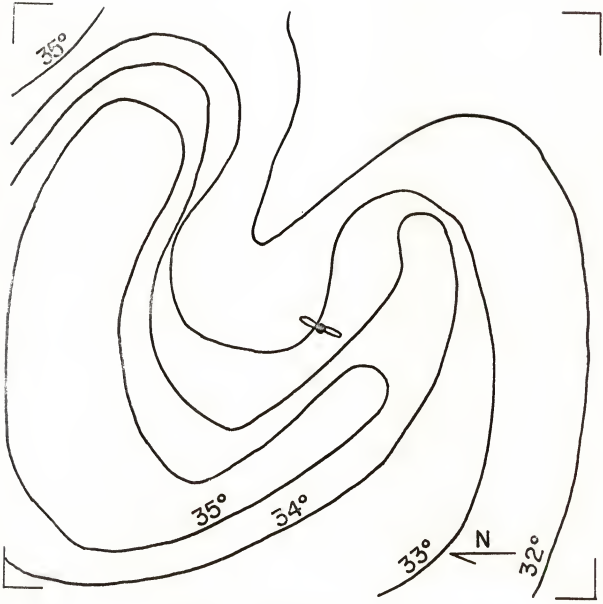

Date: December 10, 1962
Time: 10:01 PM
Level: 20 foot
Wind: Calm

Figure 43. Development of isotherm pattern following the start of the wind machine with foliage on the trees: Sixteen minutes after the start of the wind machine.



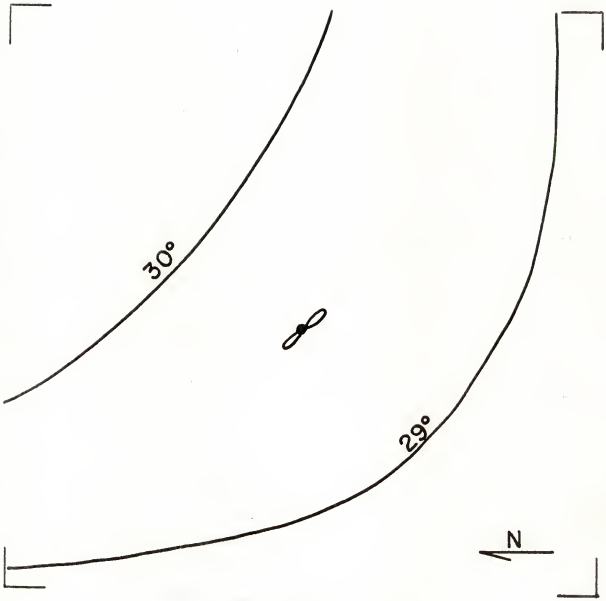

Date: December 10, 1962
Time: 10:12 PM
Level: 20 foot
Wind: Calm

Figure 44. Development of isotherm pattern following the start of the wind machine with foliage on the trees: Twenty-seven minutes after the start of the wind machine.



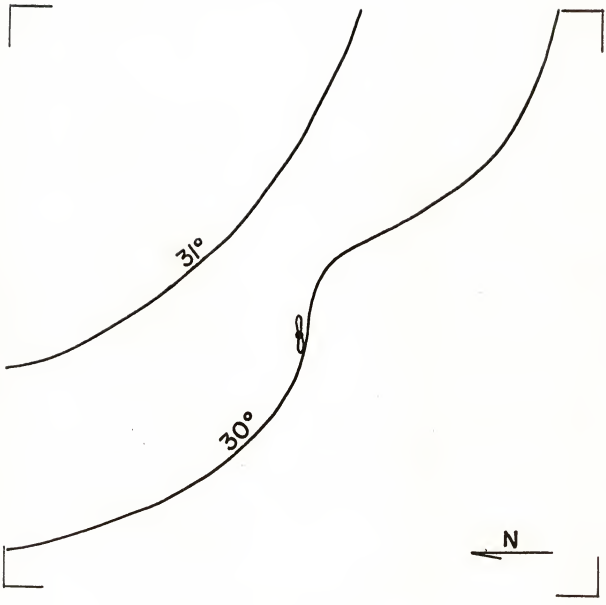

Date: December 10, 1962
Time: 10:22 PM
Level: 20 foot
Wind: Calm

Figure 45. Development of isotherm pattern following the start of the wind machine with foliage on the trees: Thirty-seven minutes after the start of the wind machine.



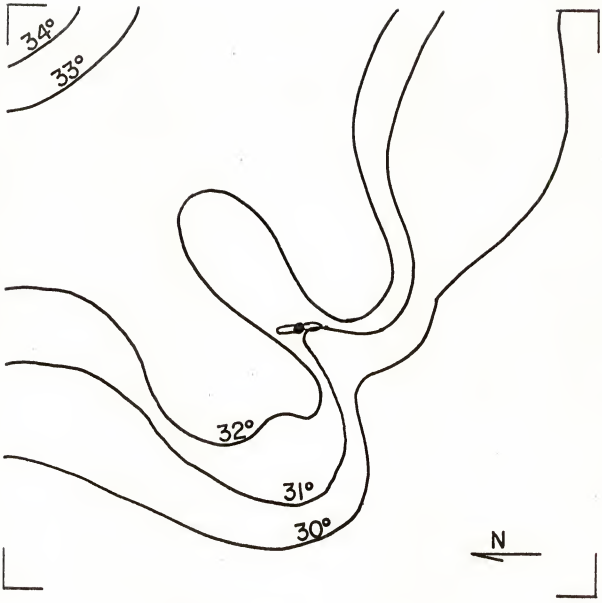

Date: December 10, 1962
Time: 9:50 PM
Level: 5 foot
Wind: Calm

Figure 46. Development of isotherm pattern following the start of the wind machine with foliage on the trees: Five minutes after the start of the wind machine.



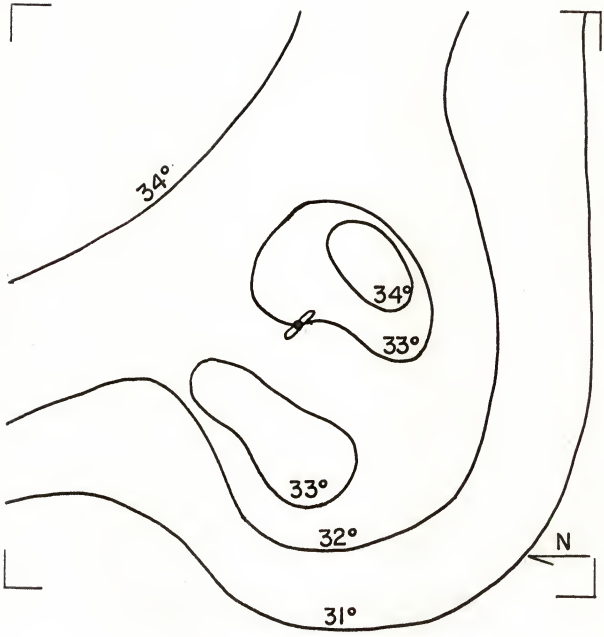

Date: December 10, 1962
Time: 9:56 PM
Level: 5 foot
Wind: Calm

Figure 47. Development of isotherm pattern following the start of the wind machine with foliage on the trees: Eleven minutes after the start of the wind machine.



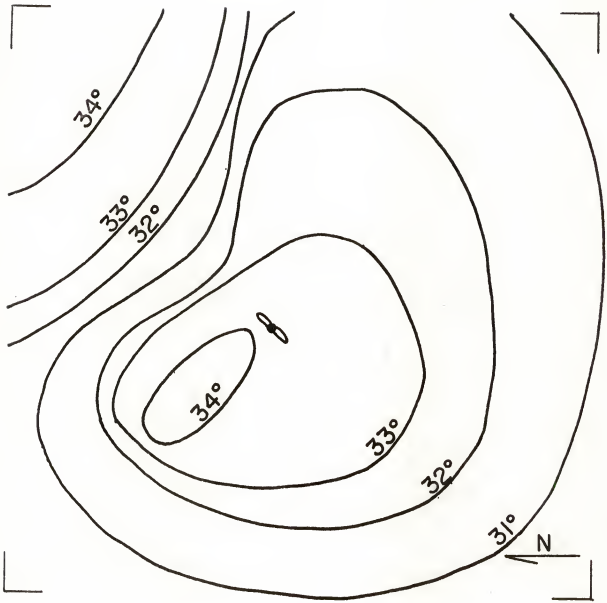

Date: December 10, 1962
Time: 10:01 PM
Level: 5 foot
Wind: Calm

Figure 48. Development of isotherm pattern following the start of the wind machine with foliage on the trees: Sixteen minutes after the start of the wind machine.




Date: December 10, 1962
Time: 10:17 PM
Level: 5 foot
Wind: Calm

Figure 49. Development of isotherm pattern following the start of the wind machine with foliage on the trees: Thirty-two minutes after the start of the wind machine.




Date: December 10, 1962
Time: 10:22 PM
Level: 5 foot
Wind: Calm

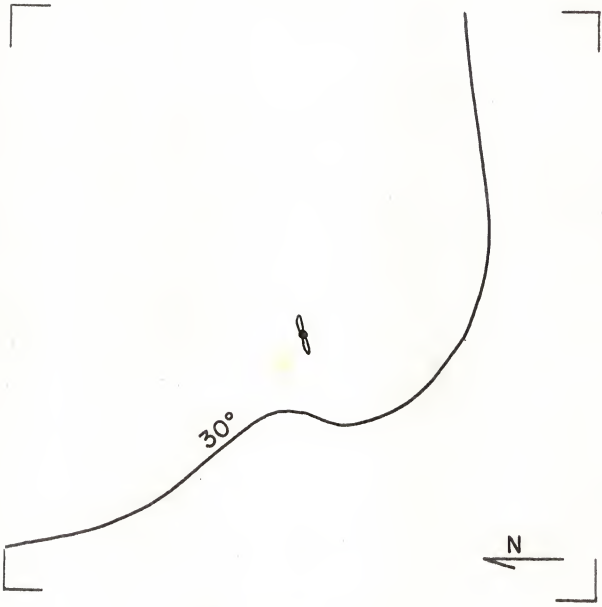
Figure 50. Development of isotherm pattern following the start of the wind machine with foliage on the trees: Thirty-seven minutes after the start of the machine.

calculated from data taken on December 11, 1962, while the leaves were in a live, healthy condition. Similar data taken with defoliated trees were plotted for January 4, 1963.

The response time at 20 feet still was in the range of 10 to 15 minutes as it was with leaves present. The response time at the 5-foot level appeared to have been shortened by 5 to 10 minutes. The time of response occurred in approximately 25 minutes or less from the time the machine was started. The time period was shortened from 5 to 10 minutes when compared against trees with foliage. The development of isotherms at the 5-foot level (Figs. 51 through 55) can be compared with those at the 20-foot level (Figs. 56 through 60) for the same time period.

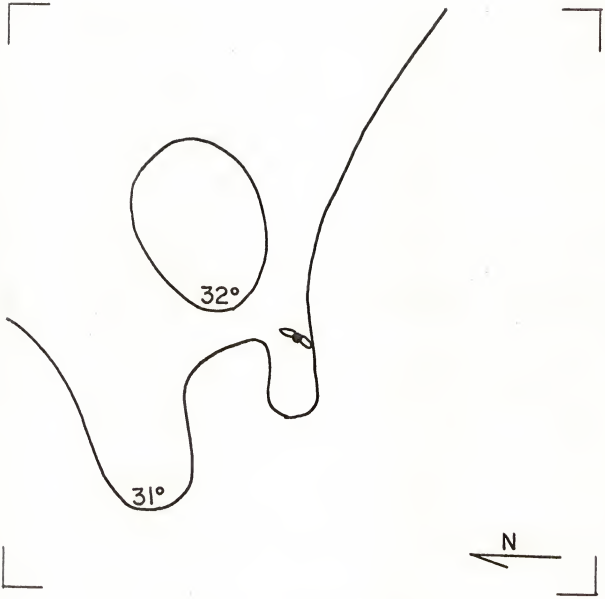
The faster response time at the 5-foot level without leaves was due to the increased penetration of the jet into the tree zone. The leaves undoubtedly offered considerable resistance to penetration by their presence on the trees. More time was required to form eddy currents and to move these currents down among the trees to the 5-foot level. Without the presence of the leaves, this penetration and the mixing process was considerably shortened.

Vertical Profile Patterns: Temperature profiles in the horizontal form have been discussed in previous sections of this paper. By taking the readings from 2 legs of the thermistor towers at one time, either NE-SW or NW-SE, vertical profiles or cross sections can be made. Isotherms can be drawn to show the temperature profiles in 2 cross sections at the same relative time.



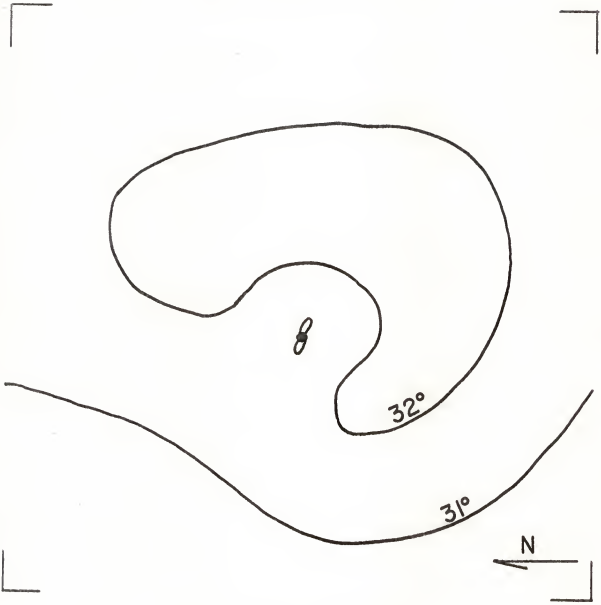

Date: January 4, 1963
Time: 2:25 AM
Level: 5 foot
Wind: Calm

Figure 51. Development of isotherm pattern following the start of the wind machine in defoliated trees: Five minutes after the start of the machine.



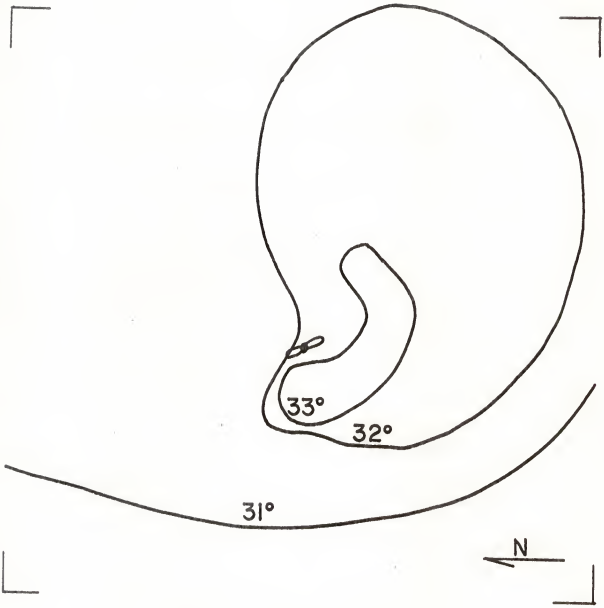

Date: January 4, 1963
Time: 2:35 AM
Level: 5 foot
Wind: Calm

Figure 52. Development of isotherm pattern following the start of the wind machine in defoliated trees: Fifteen minutes after the start of the machine.



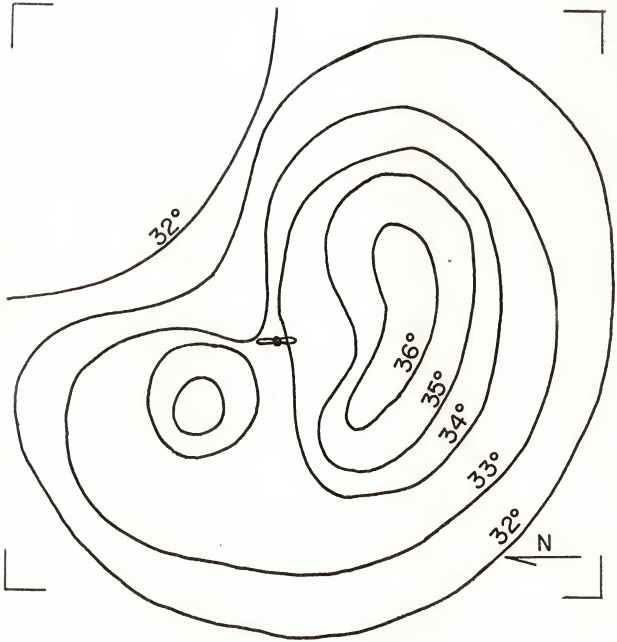

Date: January 4, 1963
Time: 2:40 AM
Level: 5 foot
Wind: Calm

Figure 53. Development of isotherm pattern following the start of the wind machine in defoliated trees: Twenty minutes after the start of the machine.



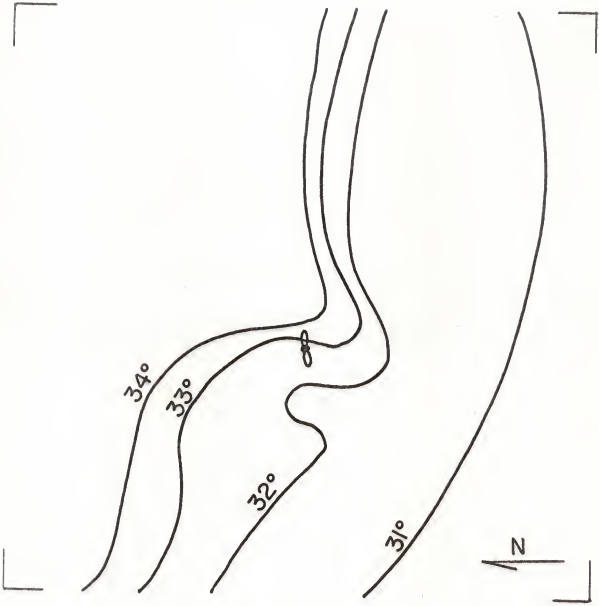

Date: January 4, 1963
Time: 2:45 AM
Level: 5 foot
Wind: Calm

Figure 54. Development of isotherm pattern following the start of the wind machine in defoliated trees: Twenty-five minutes after the start of the machine




Date: January 4, 1963
Time: 2:55 AM
Level: 5 foot
Wind: Calm

Figure 55. Development of isotherm pattern following the start of the wind machine in defoliated trees: Thirty-five minutes after the start of the machine.

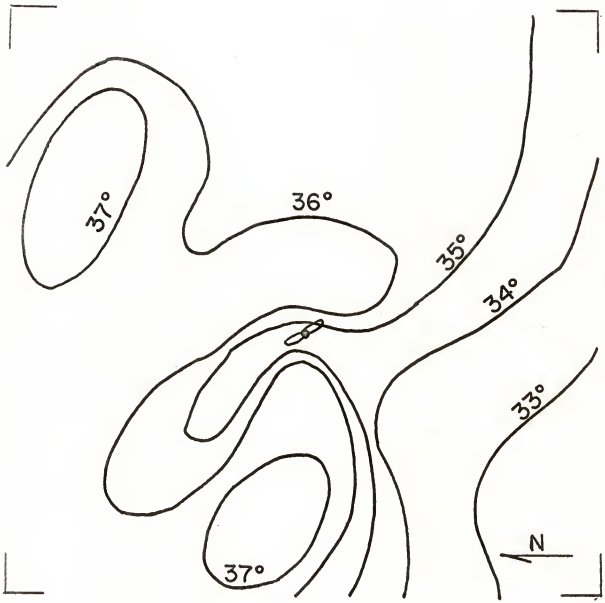



Date: January 4, 1963
Time: 2:25 AM
Level: 20 foot
Wind: NNW, 1-2 mph

Figure 56. Development of isotherm pattern following the start of the wind machine in defoliated trees: Five minutes after the start of the machine.

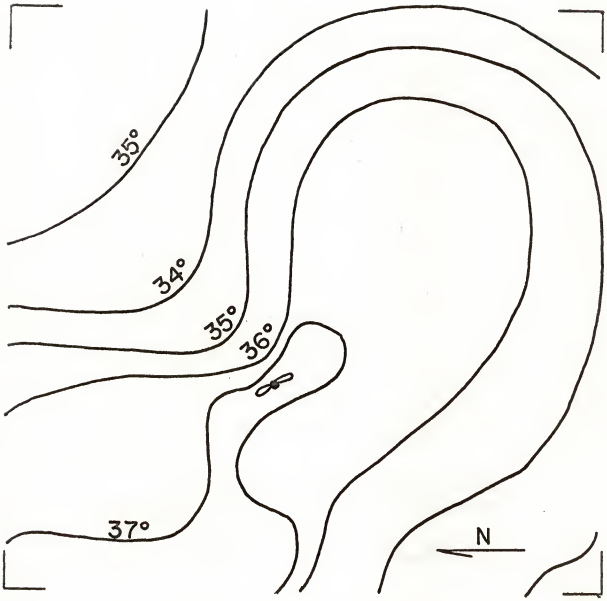
Date: January 4, 1963
Time: 2:30 AM
Level: 20 foot
Wind: NNW, 1-2 mph

Figure 57. Development of isotherm pattern following the start of the wind machine in defoliated trees: Ten minutes after the start of the machine.



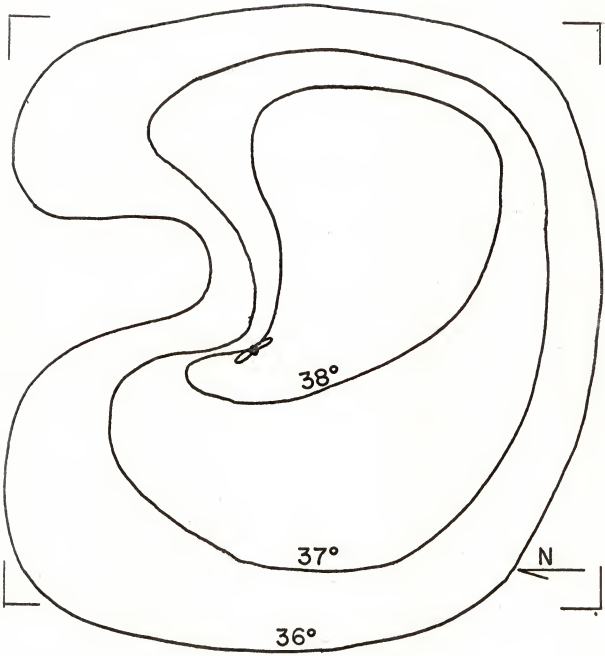

Date: January 4, 1963
Time: 2:35 AM
Level: 20 foot
Wind: NNW, 1-2 mph

Figure 58. Development of isotherm pattern following the start of the wind machine in defoliated trees: Fifteen minutes after the start of the machine.




Date: January 4, 1963
Time: 2:40 AM
Level: 20 foot
Wind: NNW, 1-2 mph

Figure 59. Development of isotherm pattern following the start of the wind machine in defoliated trees: Twenty minutes after the start of the machine.




Date: January 4, 1963
Time: 2:55 AM
Level: 20 foot
Wind: NNW, 1-2 mph

Figure 60. Development of isotherm pattern following the start of the wind machine in defoliated trees: Thirty-five minutes after the start of the machine.

Figs. 61 and 62 show 2 such cross sections at 11:30 PM, on December 10, 1962. Two definite reactions were taking place in Fig. 61 which should be noted. In the NE quadrant, or to the left of the page, the cooler air can be seen moving in under the warmer air above it toward the wind machine base. At the time the cross sections were made, the jet was just approaching the SE quadrant in a counterclockwise direction. The NE quadrant was the area which the wind machine had passed over 3-1/2 to 4 minutes previously. The jet reaction and eddy currents were less active in this area than in any other. Thus, the cool air met less resistance than in any other quadrant.

The second point in Fig. 61 is the penetration of warm air from above that can be noted in the SW quadrant. The turning jet had passed these measuring points and was blowing on the SE leg of the thermistor system. Fig. 61 shows the penetration action of the jet and how this jet pushed back the layers of cooler air in front of it. The jet pushed back the colder air and dug a hole in the atmosphere near the ground.

The other 2 quadrants for the same time period are shown in Fig. 62. Here again are seen some interesting aspects in the vertical profile. The NW quadrant had more or less stabilized with most of the turbulent action already completed. The cooler intruding air, having been pushed back out of the figure, leaves relatively stable isotherms intact. The SE quadrant was being disturbed by the

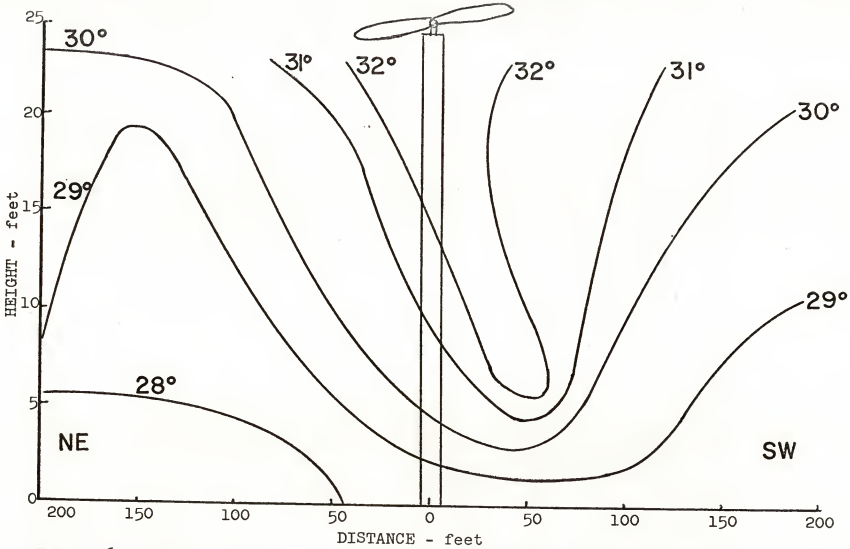



Figure 61. Vertical isotherms at 11:00 PM on December 10, 1962. Profile traversing test area from NE to SW. Machine blowing toward the south.

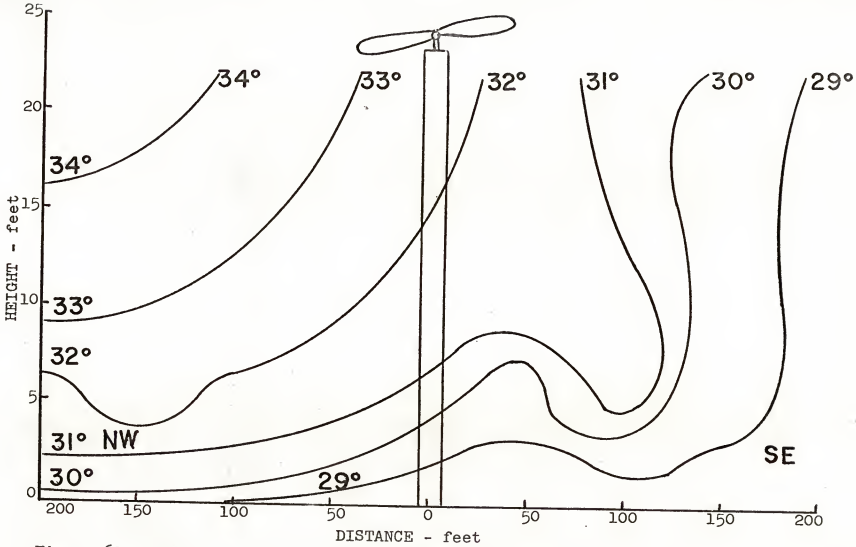



Figure 62. Vertical isotherms at 11:00 PM on December 10, 1962. Profile traversing test area from NW to SE. Machine blowing toward the south.

penetration of the jet, and the cold air was beginning to be moved back or incorporated into the jet as it moved outward and downward.

Similar cross sections were drawn for the night of January 4, 1963, when the jet was not blowing on any of the thermistor legs but was aimed directly east. The cold air intrusion can be noted in 2 quadrants, the NE and the NW (Figs. 63 and 64). The downward and outward force of the jet can be observed in the SW and SE quadrants. Temperatures were higher in the SE quadrant indicating a more recent mixing of the air.

From these vertical profiles and numerous others not shown here, a good sequence of the action of the wind machine can be developed. The wind machine pushes the jet cone outward and downward. At the same time, the jet is bent back by the resistance of the rough surface and atmosphere. The cool air is piled up in front of the jet cone and pushed outward away from the machine. Some of this piled up air is incorporated into the jet cone as it expands. As the force in the turning jet weakens, the cooler air tends to push back on the outer edges until the cooler air begins to move back in toward the machine base. Usually this is accomplished by moving in at the levels close to the ground where radiation cooling is also taking place. About the time this inward movement mounts momentum, the turning jet again pushes warmer air against the intrusion and rolls it back. This is a complete cyclic action in the vertical profile.

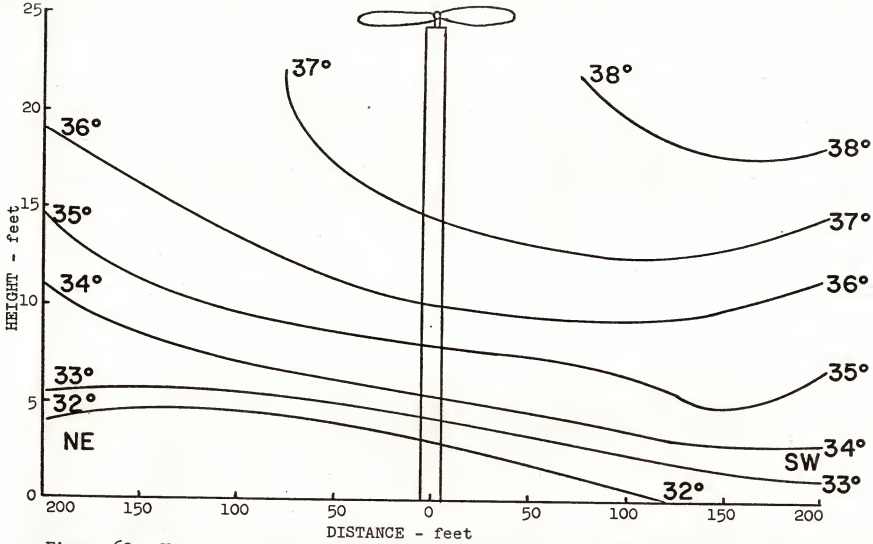



Figure 63. Vertical isotherms at 4:00 AM on January 4, 1963. Profile traversing test area from NE to SW. Machine blowing toward the SE.

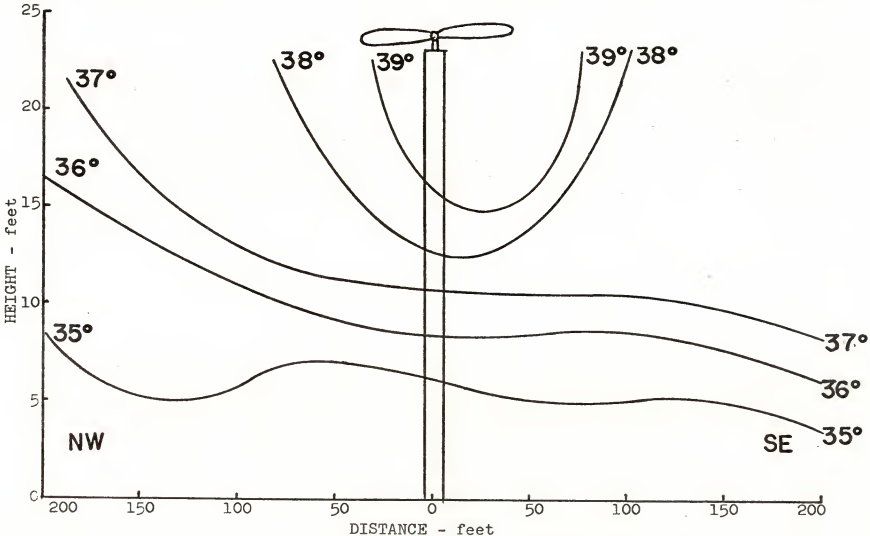



Figure 64. Vertical isotherms at 4:00 AM on January 4, 1963. Profile traversing test area from NW to SE. Machine blowing toward the SE.

Relationship Between Area of Protection and Inversion Strength: Researchers have noted over the years that inversions are essential in satisfactory operation of wind machines. Figs. 65, 66, 67 and 68 show the relationship of the inversion strength to the area of protection obtained with a wind machine in operation when leaves are present on the trees.

Fig. 65 shows the area over which one could expect to get a $1^{\circ}$ F rise in temperature at any given inversion strength. Since the maximum recorded inversion was approximately $9^{\circ}$ F, the highest point shown on this figure will be at this point. The $9^{\circ}$ F inversion gave approximately 10 acres of protection at the $1^{\circ}$ F level. Values can be calculated for stronger inversions by use of the equation $Y = 1.244X - 1.18$. Figs. 66, 67 and 68 give the same information for the $2^{\circ}$, $3^{\circ}$ and $4^{\circ}$ F protection areas. All the information shown in the 4 above mentioned figures was taken prior to the 1962 freezes while the trees were fully foliated.

Following the freezes in December, 1962, similar data were taken and plotted for defoliated trees (Figs. 69, 70, 71 and 72). With the leaves gone from the trees, the area of protection was reduced slightly to 8.66 acres rather than the previous 10 acres found with leaves present. This relationship holds true at the other 3 temperature levels also.

From the 2 groups of figures, we can assume that there

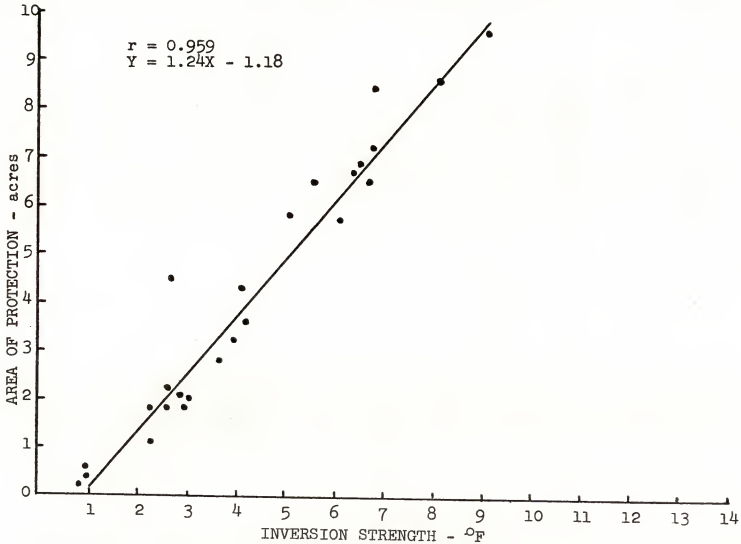



Figure 65. The area of 1° F protection provided by the wind machine as influenced by the inversion strength in the first 50 feet.

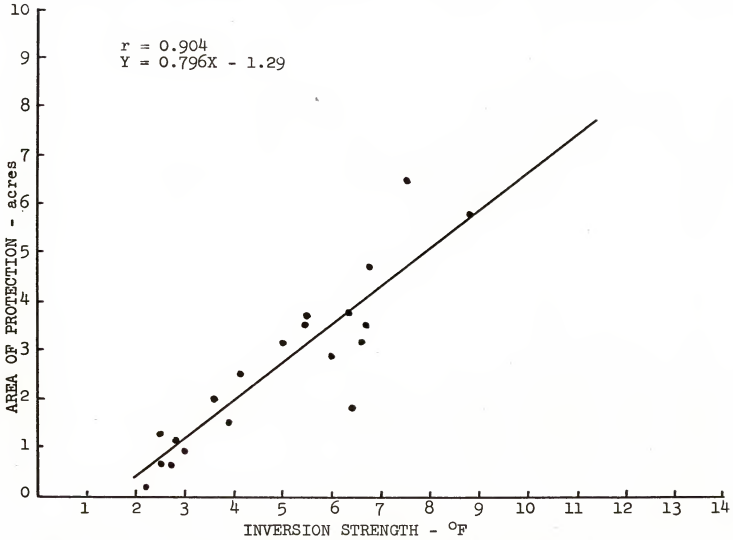



Figure 66. The area of 2° F protection provided by the wind machine as influenced by the inversion strength in the first 50 feet.

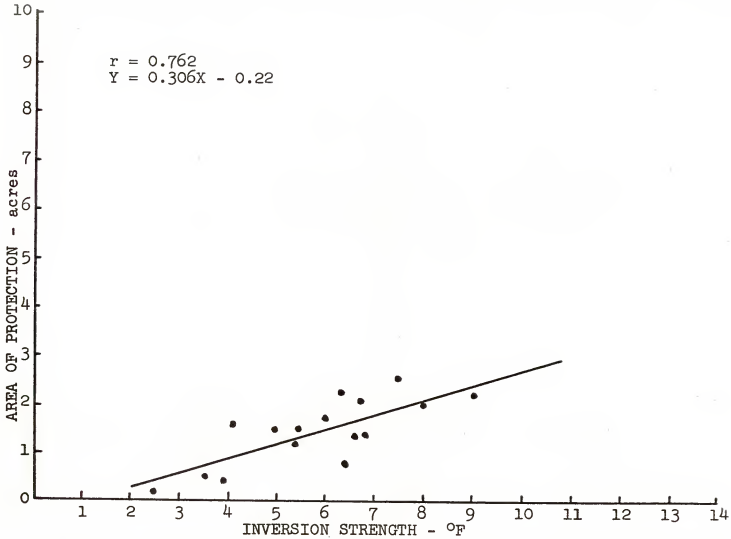



Figure 67. The area of 3° F protection provided by the wind machine as influenced by the inversion strength in the first 50 feet.

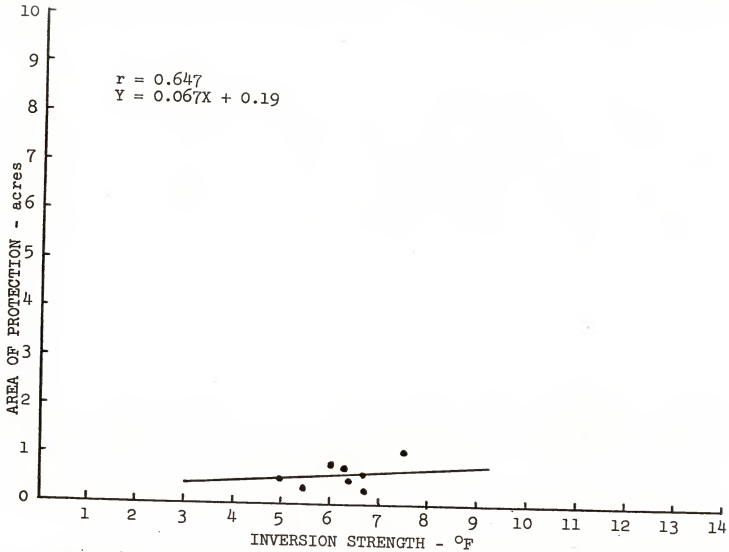



Figure 68. The area of 4° F protection provided by the wind machine as influenced by the inversion strength in the first 50 feet.

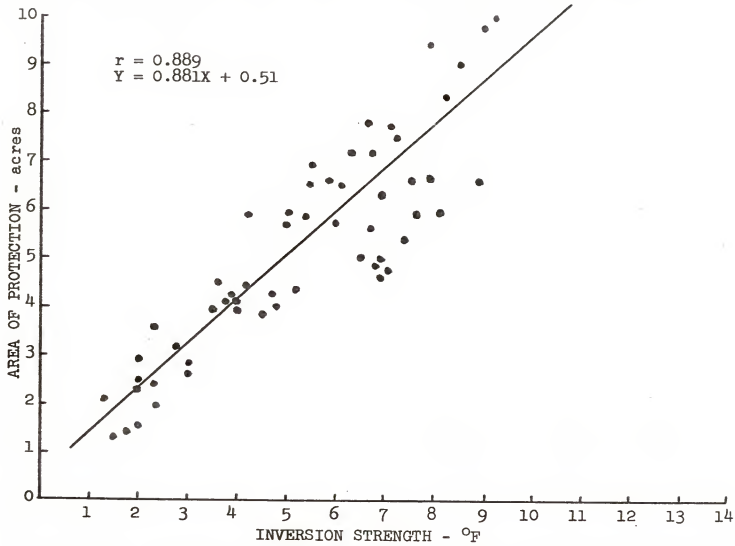



Figure 69. The area of 1° F protection provided by the wind machine as influenced by the inversion strength in the first 50 feet.

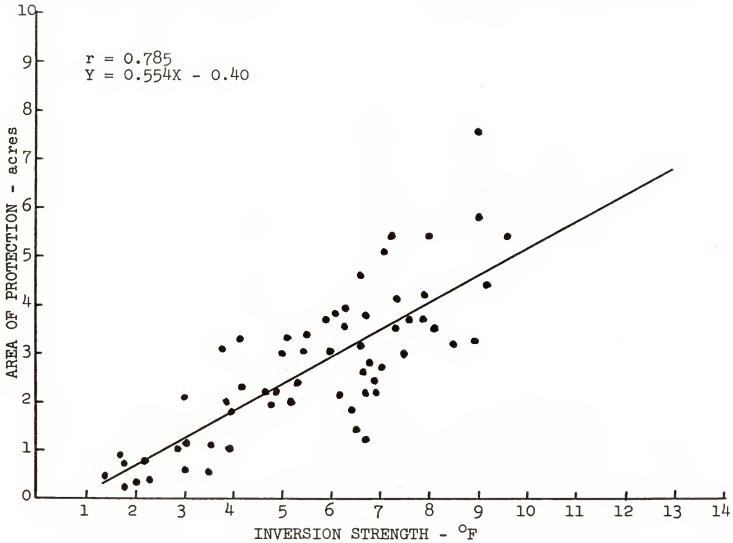



Figure 70. The area of 2°F protection provided by the wind machine as influenced by the inversion strength in the first 50 feet.

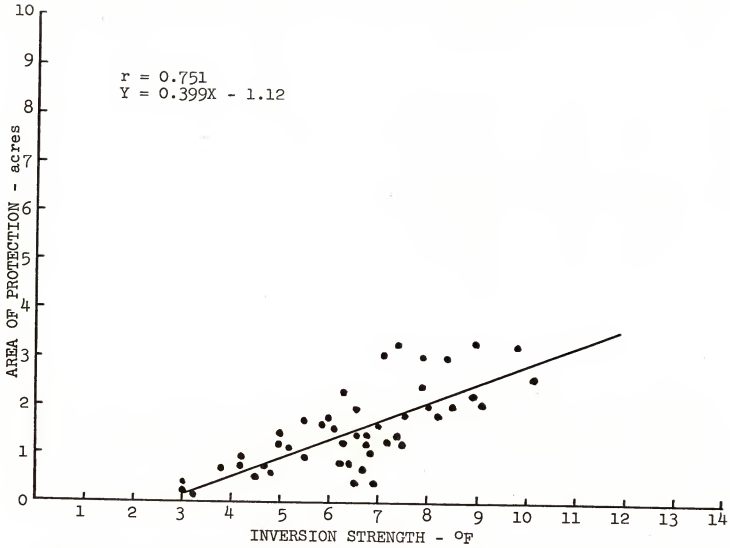



Figure 71. The area of 3° F protection provided by the wind machine as influenced by the inversion strength in the first 50 feet.

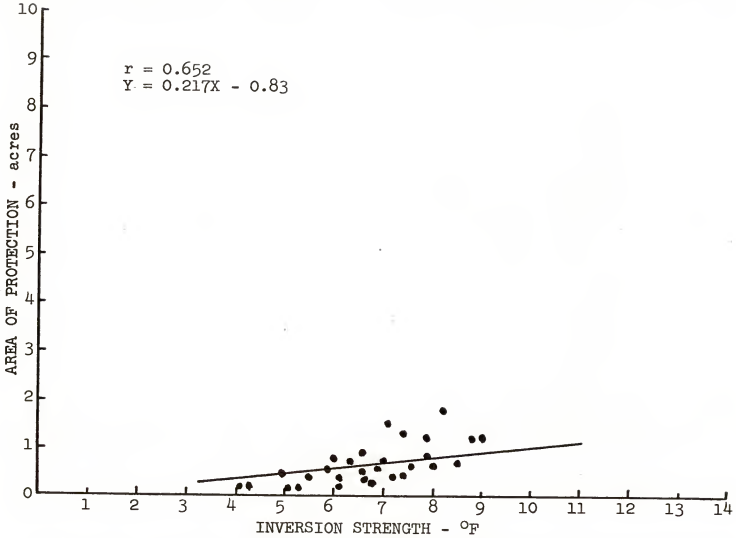



Figure 72. The area of 4° F protection provided by the wind machine as influenced by the inversion strength in the first 50 feet.

is a relationship between the inversion strength and the area of protection. Fig. 73 shows the number of acres which were protected at the 4 protection levels when inversions were at the strength indicated. This figure gives values for the grove when the leaves were present on the trees.

For example, if there was an inversion of $8^{\circ}$ F, the area of protection at $2^{\circ}$ F which could be expected would be approximately 4.8 acres. The area of $1^{\circ}$ F protection with the same inversion would be 8.4 acres.

A similar chart was prepared for trees without leaves (Fig. 74). It can be noted that the area of protection with small inversions was larger without leaves that it was with leaves present. As the inversion strength increased, the reverse situation occurred. At a $6^{\circ}$ F inversion strength, the 2 sets of values were almost identical. At $8^{\circ}$ F and $10^{\circ}$ F inversion strengths, the area protected was greater when foliage was present. This was due to greater roughness which caused more eddy current action in the tree area. The mixing action carried a greater distance and probably continued on a longer period of time incorporating more of the surrounding air.

Relationship Between Area of Protection and Wind Speed: Assuming that the wind speed is related to the inversion strength and inversion formation, then there should be a relationship between the area of protection and the wind speed. Figs. 75, 76 and 77 were plotted to determine if such a relationship did exist. These figures show the

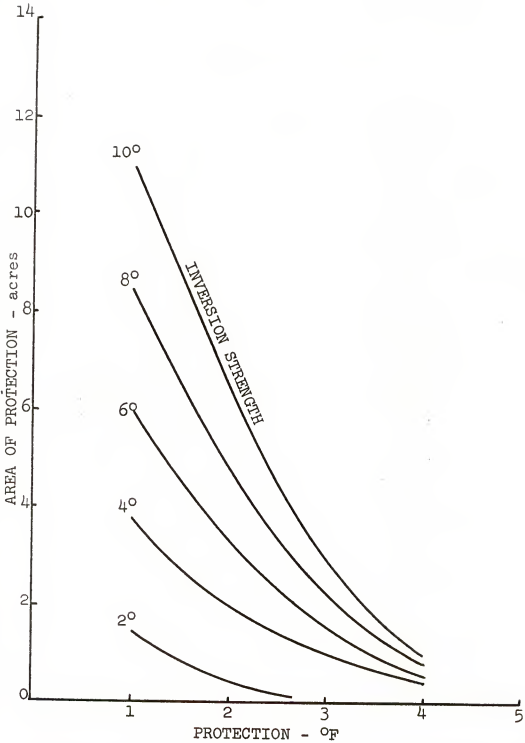



Figure 73. An estimate of the area of protection of 1, 2, 3 and 4° F that can be expected at indicated inversion strengths when leaves were present on the trees.

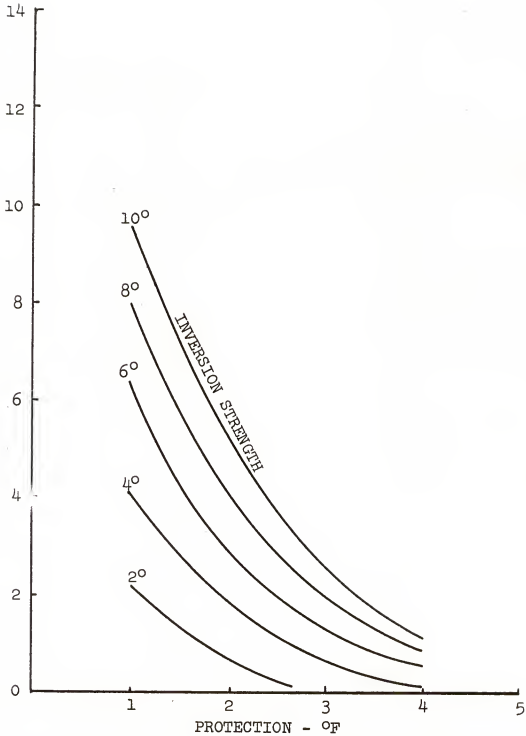



Figure 74. An estimate of the area of protection of 1, 2, 3 and 4° F that can be expected at indicated inversion strengths when leaves were not present on the trees.

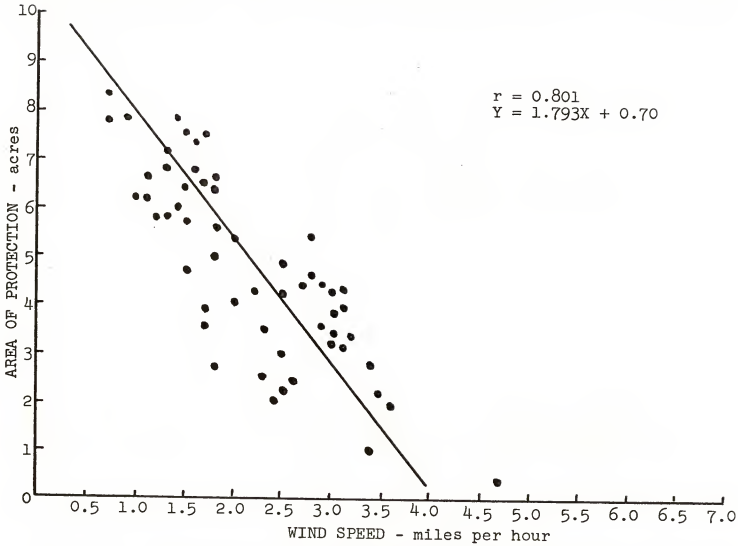



Figure 75. The area of 1° F protection provided by the wind machine as influenced by the wind speed in the first 50 feet.

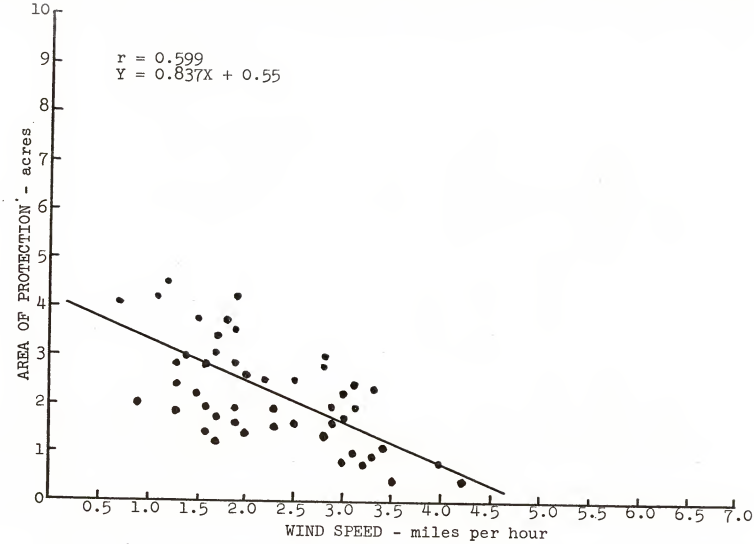



Figure 76. The area of 2° F protection provided by the wind machine as influenced by the wind speed in the first 50 feet.

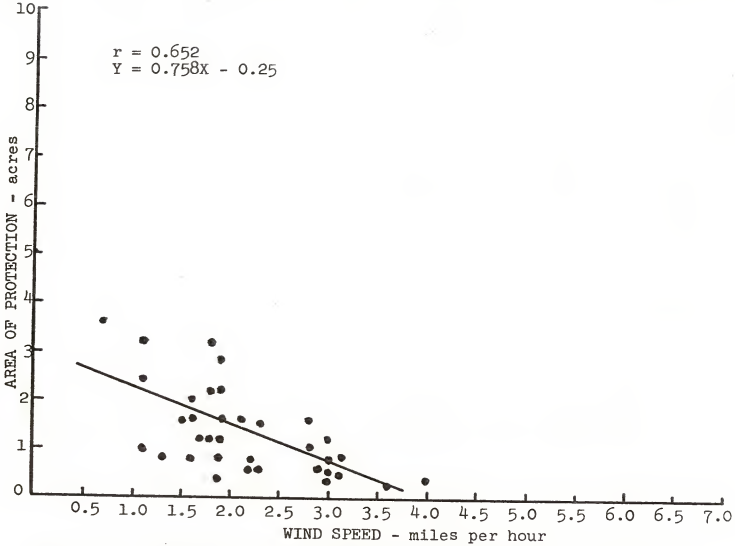



Figure 77. The area of 3° F protection provided by the wind machine as influenced by the wind speed in the first 50 feet.

areas of protection at the $1^{o}$, $2^{o}$ and $3^{o}$ F levels with relation to the natural wind speed.

The area of protection in all 3 cases was reduced rapidly at the wind speed increased. In all fairness, it should be noted here, that these were average wind speeds, not gusts up to 4 mph. All protective value appears to have been lost in the vicinity of 4 to 5 mph. Wind data taken from this same site indicated that there was seldom a constant wind of 4 mph during the nocturnal hours. In order to obtain such an average, the wind would have had to reach peaks of 5 to 7 mph interspersed with prolonged periods of 2 mph.

The protection area of $1^{o}$ F covers more than 8 acres with winds less than 1 mph (Fig. 75). As the wind increased to 2 mph, the acreage was reduced to approximately 4 acres. Winds of 4 mph or greater reduced the area of protection to almost zero.

The natural mixing that occurs when winds reach 4 mph or greater leave the wind machine in the position of performing mixing that is already being done. Natural mixing at 4 mph or greater accomplishes the same results that the wind machine could do if conditions were stable in the profile. The natural mixing minimizes the inversion strength or completely breaks up the inversion so that the wind machine does not have a heat source. Without this source of heat, the wind machine is of no benefit.

## Effect of the Wind Machine on the Microclimate

Radiation Measurements: The effect of the wind machine on radiation equipment and values was apparently very small. Some slight differences were observed and recorded in the radiation values with and without the wind machine in operation (Table 2).

The Beckman-Whitley radiometers were equipped with forced-air blower units to maintain the recording surfaces at or near the ambient air temperature. Even with the blowers present and in operation, there were still some fluctuations in the readings that could be directly associated with the wind machine rotation cycle. It was apparent that the wind machine, by passing large volumes of air directly over the radiometer plate surfaces, did modify the plate temperature, thus giving lower readings than the average for the period when the plates were only under the influence of the self-contained blower unit.

The data in Table 2 show a lower net radiation with the wind machine in operation in all instances except the night of January 21-22, 1963, when a slight increase was observed. The incoming radiation did not show any pattern in readings indicating increases in some instances and decreases in other instances.

The outgoing radiation with the exception of 1 night, December 12-13, 1962, showed a reduction when the wind machine was put into operation.

Table 2

Radiation values with and without the wind machine in operation

| Date | Radiation (Langleys per minute) | | | | | |
|---|---|---|---|---|---|---|
| | Net | | Incoming | | Outgoing | |
| | Without | With | Without | With | Without | With |
| 12/12-13/62 | -0.196 | -0.187 | 0.256 | 0.273 | -0.452 | -0.460 |
| 12/13-14/62 | -0.167 | -0.146 | 0.299 | 0.304 | -0.466 | -0.450 |
| 1/3-4/63 | -0.174 | -0.163 | 0.325 | 0.313 | -0.499 | -0.476 |
| 1/7-8/63 | -0.159 | -0.155 | 0.311 | 0.303 | -0.470 | -0.458 |
| 1/21-22/63 | -0.166 | -0.169 | 0.324 | 0.312 | -0.490 | -0.481 |
| 1/24-25/63 | -0.155 | -0.149 | 0.311 | 0.314 | -0.466 | -0.463 |

Soil Heat Flux: The wind machine had no effect on the soil heat flow plates that was measureable. These plates were covered with 1/2 inch of soil and were not in direct contact with any moving air from the wind machine. Data on soil heat flow measurements with and without the wind machine in operation are shown in Table 3.

Problems occurred on the night of December 12-13, 1962, with the soil heat flow plates when the surface soil down to about a 2-inch depth was frozen. Moisture between the phenolic layers within the plate was also frozen, causing expansion an damage to the sensory points. The same plates were used the remainder of the season and continued to work and give data. Tests run the next year with a new set of plates tend to indicate the 1962-63 data were valid even though the plates suffered some damage.

Point 5 in Table 3 was located in an open area between citrus trees open to the sky except for the 1/2-inch soil cover over the plate. Point 7 was located 1/2 inch deep in the soil under the canopy of a citrus tree and was hidden from direct contact with the sky.

Inversion Strength: The operation of a wind machine has a similar effect on the inversion strength to that of natural convection. The mixing of the air from 40 to 50 feet with the air below this zone by induced convection has a tendency to lower the inversion temperature at the upper levels. January 4, 1963 (Fig. 78), was a good example of this effect. Beginning at 12:30 AM, the wind began a

Table 3

Soil heat flow measurements with and without the wind machine in operation

| Date | Soil heat flow (Langleys per minute) | |
|---|---|---|
| | Without wind machine | With wind machine |
| Point # 5 * | | |
| 12/12-13/62 | 0.055 | 0.055 |
| 12/13-14/62 | 0.035 | 0.035 |
| 1/3-4/63 | 0.025 | 0.025 |
| 1/7-8/63 | 0.020 | 0.020 |
| 1/21-22/63 | 0.089 | 0.089 |
| 1/24-25/63 | 0.079 | 0.079 |
| Point # 7 ** | | |
| 12/12-13/62 | 0.023 | 0.023 |
| 12/13-14/62 | 0.022 | 0.023 |
| 1/3-4/63 | 0.030 | 0.030 |
| 1/7-8/63 | 0.032 | 0.032 |
| 1/21-22/63 | 0.039 | 0.039 |
| 1/24-25/63 | 0.032 | 0.032 |

* Point # 5 was located under 1/2 inch of soil in an open area between two citrus trees.

** Point # 7 was located under 1/2 inch of soil beneath the canopy of a citrus tree.

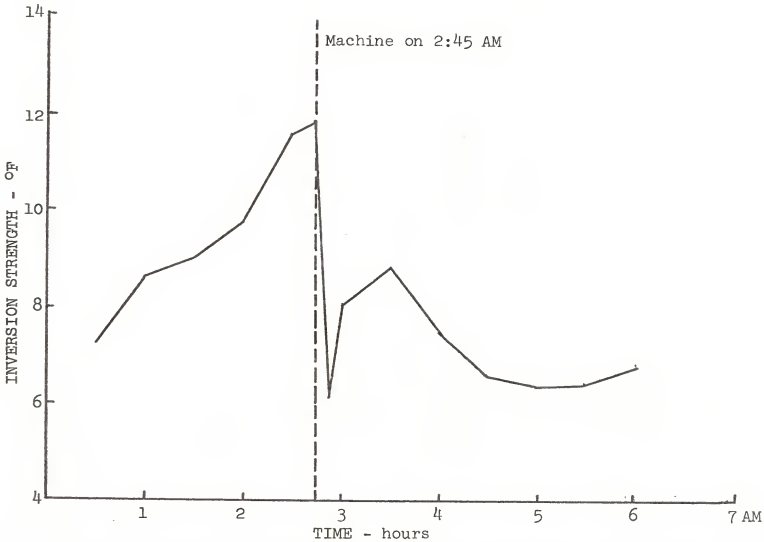



Figure 78. A comparison of the inversion strength before and after the start of the wind machine on January 4, 1963.

gradual decrease from 2 to 3 mph until it reached a completely calm period at 2:20 AM. The wind machine was started at 2:45 AM during this calm period, and the change in the inversion profile was quite drastic. The inversion between 5 and 50 feet dropped from 11.8° F to 6.2° F in less than 15 minutes and then gradually rebounded to 8.5° F. Following this rebounding action, it gradually declined to the vicinity of 6.5° F where it stayed until sunrise.

A similar situation occurred on the night of December 13-14, 1962 (Fig. 79), with an inversion of lesser magnitude and natural convection of 2 mph above the tree tops. When the wind machine was turned on, the inversion varied from 2 to 4° F depending on the natural air movement. Before the machine was started, the inversion had been 7.0° F. At midnight there was an increase in wind speed to about 5 mph, and the inversion strength was reduced from 1.7 to 0.8° F.

Fig. 80 points out the recovery of the inversion strength when the wind machine was stopped after running for a 2-hour period. When the wind machine was first initiated, the inversion was approximately 3.0° F, but after running for a short period, the temperature difference between 5 and 50 feet was only 1° F. The temperature rose after the machine was turned off to a point slightly above 2° F. When the machine was started a second time, the temperature again dropped to about the same level or maybe slightly lower than during the first run.

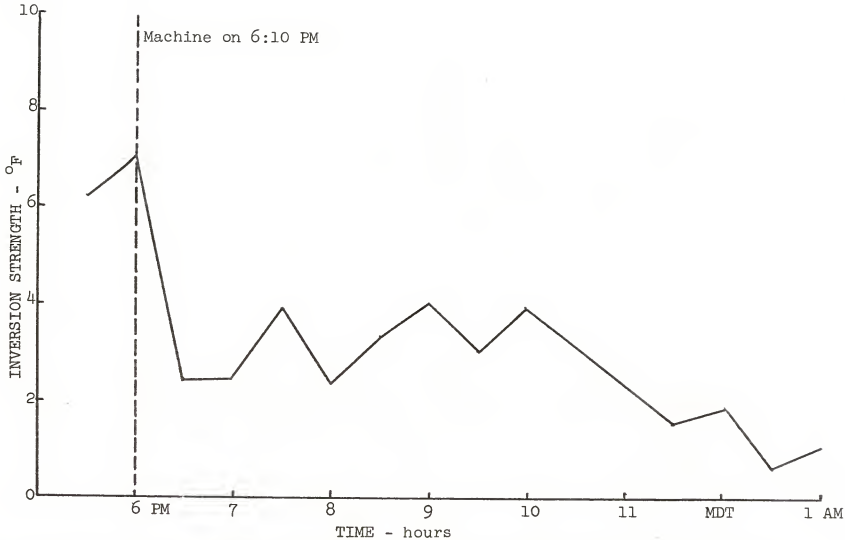



Figure 79. A comparison of the inversion strength before and after the start of the wind machine on December 13-14, 1962.

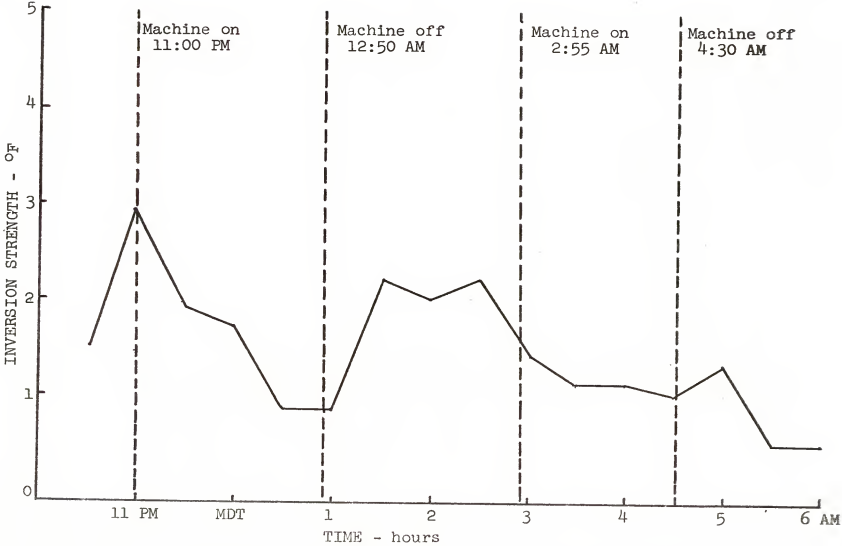



Figure 80. A comparison of the inversion strength before and after the start of the wind machine on January 24-25, 1963.

The loss in inversion strength was not at all unexpected since the air at machine height and above was the source of supply of warmth on which the machine depended. The air from this area was mixed with the cooler air near the ground and trees. As this mixing took place, the air near the ground became warmer as a result of the mixing with warm air from above. The inverse situation was also true. Some of the cool air near the ground was incorporated into the jet, and as the jet expanded outward, it also expanded upward. This had a tendency to cool the air in the upper layers. Usually the air above the propeller hub was reduced in temperature whereas the layer below it showed a temperature increase.

Wind Speed: The influence of the wind machine on the wind speed is difficult to ascertain since the wind speed was not recorded outside the test area with the machine in operation. Table 4 gives wind speeds before starting the wind machine and after it was started at distances of 100, 200 and 300 feet from the machine base. Both the 5-and 20-foot height speeds are given. The night of December 10, 1962, gave the best chance to measure the wind output by the wind machine because the air was calm at 5 and 20 feet. Readings at the 100-foot distance are missing because of wiring problems. The 20-foot average wind speed at the 200-foot tower was 1.89 mph whereas it was only 1.54 mph at the 300-foot tower. A reduction from 1.16 mph to 0.57 mph was noted during the same period at the 5-foot level.

Table 4

Effect of the wind machine on the average wind speed

| Date | Height (ft) | Average wind speed (mph) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Before starting | | | After starting | | |
| | | Distance from wind machine | | | Distance from wind machine | | |
| | | 100' | 200' | 300' | 100' | 200' | 300' |
| 12/10/62 | 5 | - | 0.00 | 0.00 | - | 1.16 | 0.57 |
| | 20 | - | 0.00 | 0.00 | - | 1.89 | 1.54 |
| 12/12/62 | 5 | - | 1.79 | 1.02 | - | 1.80 | 1.23 |
| | 20 | - | 5.20 | 4.48 | - | 5.16 | 4.48 |
| 12/13/62 | 5 | 0.20 | 0.10 | 0.00 | 1.12 | 0.56 | 0.00 |
| | 20 | - | 2.58 | 2.24 | - | 2.68 | 1.78 |
| 1/4/63 | 5 | 0.00 | 0.00 | 0.00 | 1.34 | 0.65 | 0.10 |
| | 20 | - | 1.57 | 1.34 | - | 2.12 | 1.57 |
| 1/21/63 | 5 | 0.00 | 0.00 | 0.00 | 1.57 | 0.10 | 0.00 |
| | 20 | 1.68 | 0.78 | 1.12 | 2.80 | 1.23 | 1.12 |
| 1/24/63 | 5 | 0.50 | 0.00 | 0.00 | 1.46 | 0.10 | 0.00 |
| | 20 | 1.34 | 0.01 | 1.01 | 2.70 | 1.46 | 1.34 |
| 1/25/63 | 5 | 1.12 | 0.10 | 0.12 | 2.01 | 0.67 | 0.50 |
| | 20 | 3.14 | 2.24 | 2.14 | 4.25 | 3.58 | 2.46 |

During periods of natural convection, the effect of the wind machine can also be noted provided the average wind speeds were in the range of 0 to 3 mph. Values observed on January 21 and 24, 1963, show this effect very well. At the 100-foot tower, the average wind movement on January 24 was increased from 1.34 to 2.70 mph at the 20-foot level. At 200 feet the increase was from 1.01 to 1.34 mph. As the distance from the wind machine increased, the convective forces of the wind machine became weaker.

On nights when the average wind speed was in the range of 4.5 mph or more, the wind machine did not add to the wind speed values. The night of December 12, 1961, was such a night. Values with and without the wind machine operating were almost identical. Wind speed values for January 25, 1963, were in the range of 2 to 3 mph before the machine was started at the 20-foot level. The wind machine did increase the wind speed values on this night at the 5-and 20-foot levels approximately 1 mph near the machine.

By recording the signals from the anemometers on an event recorder, it was possible to determine the intensity of the wind as the jet passed across the anemometer towers. Each time the jet passed across, the 100-and 200-foot towers recorded its presence. The 300-foot distant tower did not record the jet on some cycles indicating the jet never reached the tower or that it was lifted over the tower.

The passage of a jet is shown in Fig. 81. Note the main air movement which is followed by 2 lesser movements

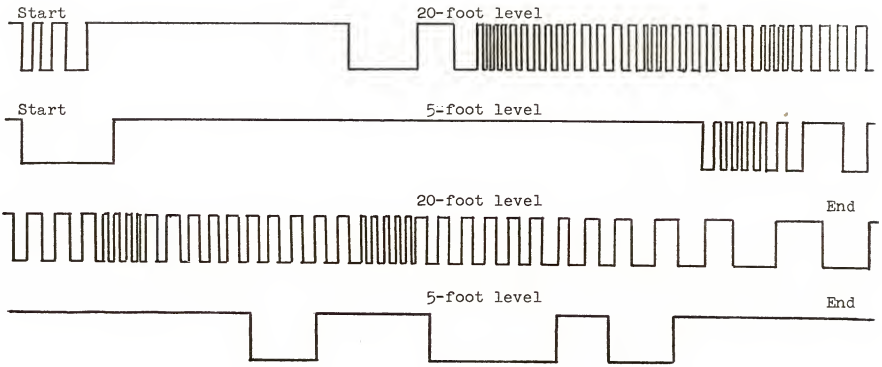



Figure 81. Diagram of the wind movement of one turning jet as recorded on an event recorder at 5 and 20 feet, 200 feet from the wind machine base under calm conditions on January 4, 1963.

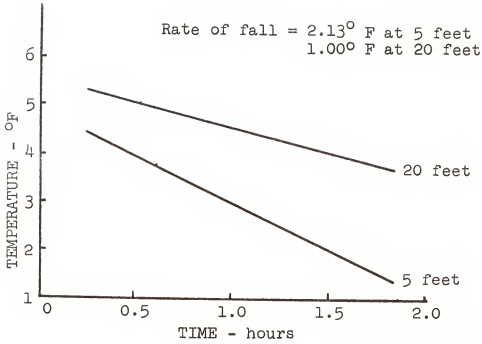
at the 20-foot level. The 5-foot level lagged considerably behind the 20-foot level and showed a much shorter period of duration. After the initial blast, the 5-foot level also showed 2 additional air movements which were of very low intensity.

The main blast was the jet itself passing the anemometer whereas the second and third movements were eddy currents following the jet passage. After the second eddy current went past, the air movement gradually slowed until no movement could be recorded at either 5 or 20 feet.

Rate of Temperature Fall With and Without Foliage: The rate of temperature fall on December 13-14, 1962 (Fig. 82), before the wind machine was started averaged 2.13° F per hour at the 5-foot level whereas the 20-foot level temperature was falling at 1.0° F per hour. When the wind machine was put into operation, there was a modification of this temperature fall. The 5-foot level rate of fall was reduced to 1.0° F per hour, and the 20-foot level was reduced to 0.90° F per hour. This indicated that the largest modification occurred at the 5-foot level.

On January 3-4, 1963 (Fig. 83), the rate of fall before the wind machine was started at the 5-foot level was approximately 2.25° F per hour and 0.94° F per hour at the 20-foot level. Both levels were modified after the wind machine was initiated to approximately 0.90° F per hour.

When the December 13-14, 1962, values were taken, the injured foliage was still present on the trees and probably



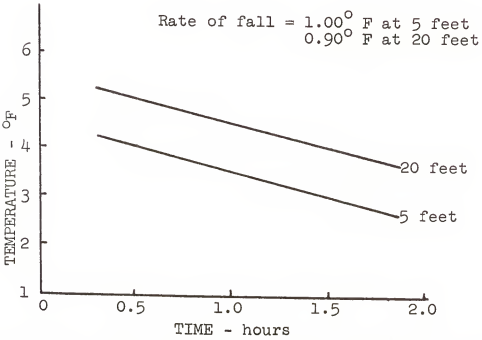
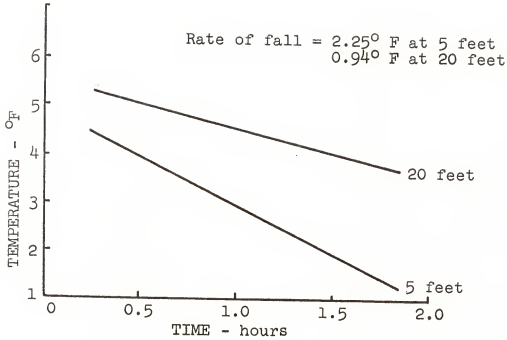




Figure 82. The comparison of the rate of temperature fall before and after the wind machine was started. Top graph shows rate before and lower graph shows rate after the machine was started.



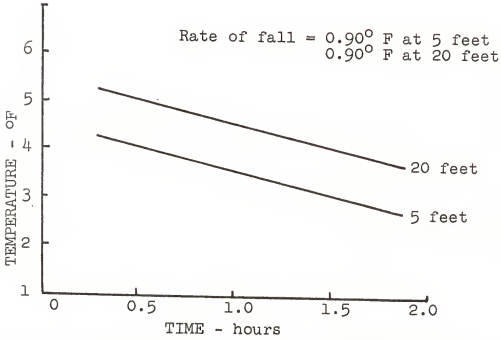




Figure 83. A comparison of the rate of temperature fall before and after the wind machine was started. Top graph shows rate before and lower graph shows the rate after the machine was started.

was responsible for the faster cooling rate at the 5-foot level. In January, all foliage was gone. The cooling rate with the air being mixed was the same at both levels.

On nights when it was calm, differences were more likely to be observed between the 5-and 20-foot levels than on nights when light winds were blowing. Light winds tend to modify the temperature fall much in the same way as the wind machine. The 2 examples given are for relatively calm nights when the maximum effect of the wind machine could be observed. When the natural wind was modifying the rate of fall, the additional influence of the wind machine was not as obvious.

Heat Budget: The wind machine, as previously stated, had little effect on the radiation and soil heat flux values. Still, the wind machine was able to decrease the rate of temperature drop close to the ground for any given time period. This means the machine must have modified the heat balance in some way other than by the radiation and soil heat fluxes.

If an inversion of sufficient magnitude is present, the wind machine is able to modify the heat balance. Wind machines do not add any heat to the grove other than the exhaust heat from the motor. This is a very small quantity in the overall picture. The wind machine is able to modify the heat balance by simply making more efficient use of the heat stored in the air above tree top height. The air in the upper layers of the inversion serves as a natural

storage area for heat or as a heat reservoir. The wind machine transfers this heat from the reservoir by forcing it down into the cooler area around the trees. By moving this air down into the grove, the wind machine is able to replace some of the heat lost by radiation cooling of the surface.

## Heat Budget and Microclimate

Radiation and Soil Heat Flux Values: Radiation and soil heat flux values were recorded during the period of the extremely cold weather in December, 1962. These data (Figs. 84 and 85) indicate some very high net radiation values, especially on the night of December 12-13. This night was an extremely cold one with clear skies, very low humidity and winds which averaged over 5 mph with gusts as high as 10 mph. It should also be noted that the incoming radiation values were low when compared to data from other nights (Figs. 86, 87, 88 and 89). The soil surface began to freeze at 9:00 PM and remained in that condition all night long. The exact depth to which the soil was frozen by 6:00 AM was estimated to be 2 inches or less. During this period, the soil heat flow plates were damaged by moisture getting between the phenolic layers and then expanding between the layers on freezing. This damage went unobserved until the plates were removed from the soil the following March. The reliability of these data is somewhat in doubt, although additional data gathered the next year with new plates were in the same range of values.

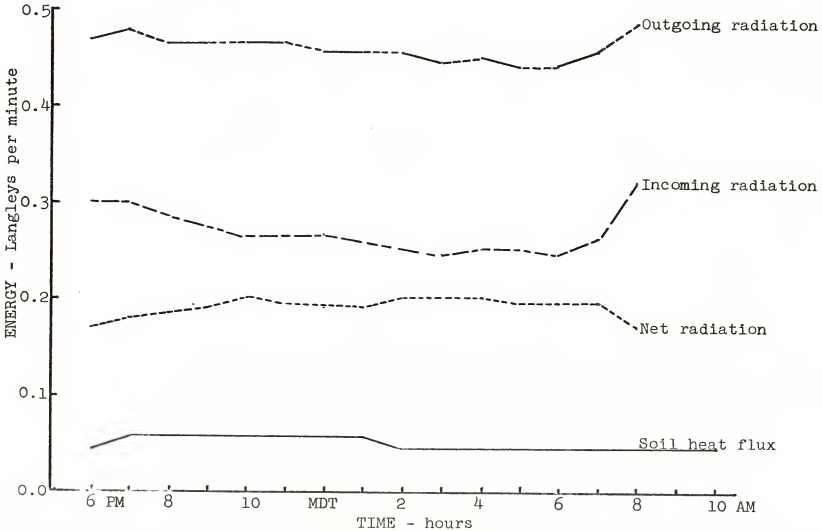



Figure 84. Radiation and soil heat flux values for December 12-13, 1962

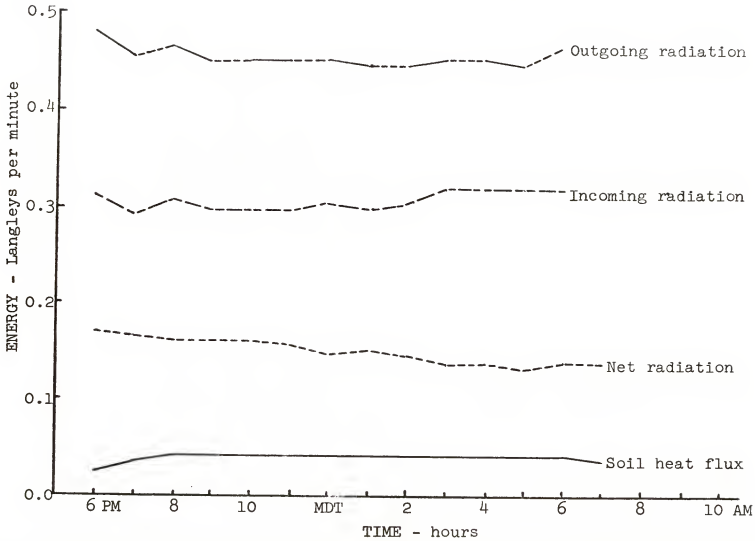



Figure 85. Radiation and soil heat flux values for December 13-14, 1962.

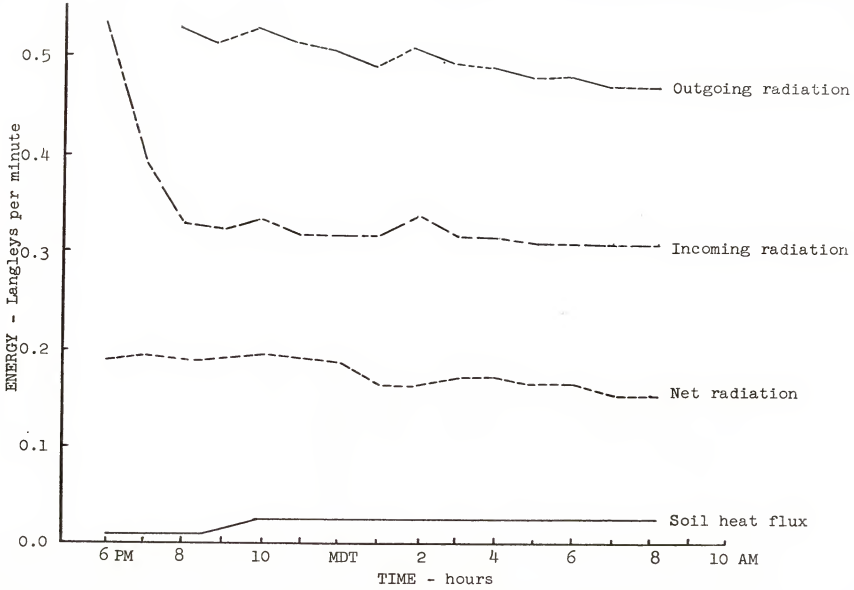



Figure 86. Radiation and soil heat flux values for January 3-4, 1963.

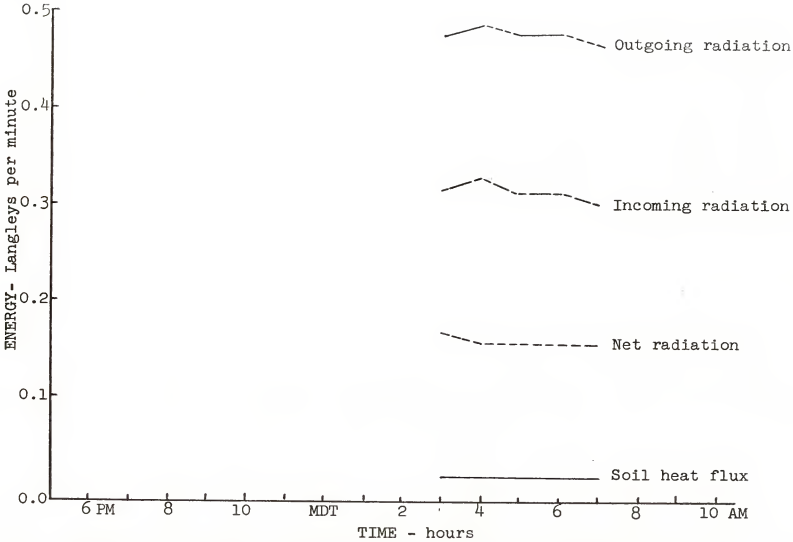



Figure 87. Radiation and soil heat flux values for January 7-8, 1963.

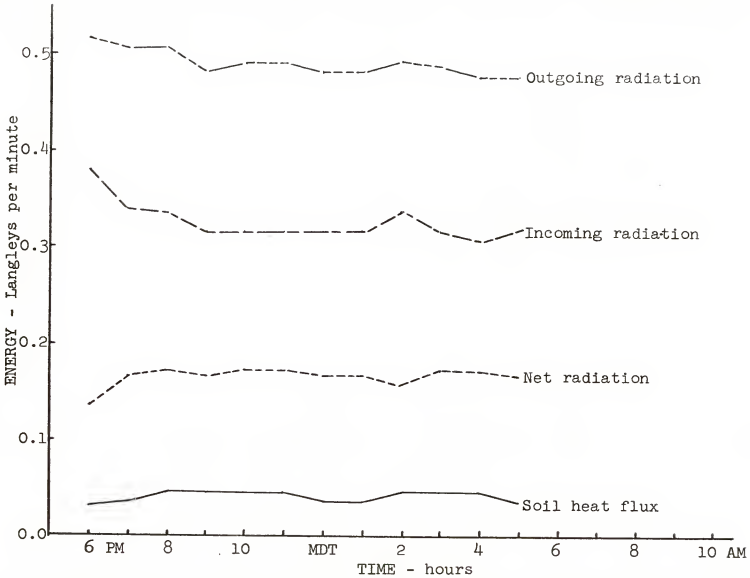



Figure 88. Radiation and soil heat flux values for January 21-22, 1963.

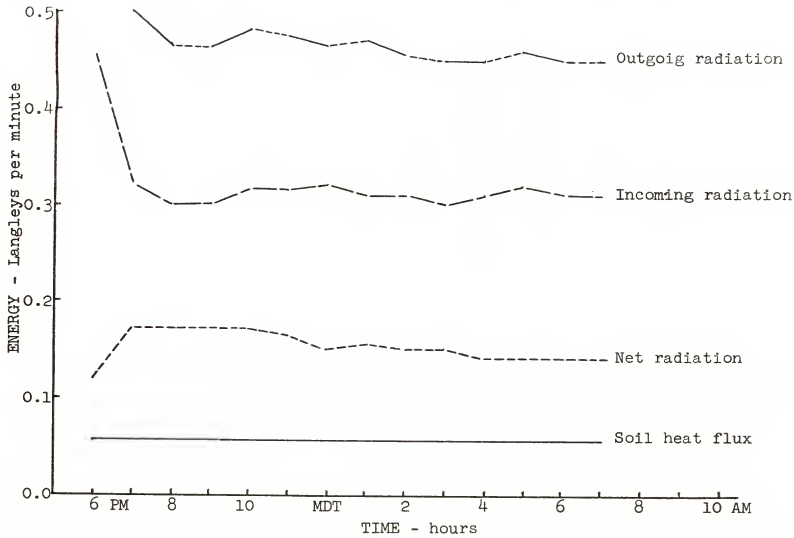



Figure 89. Radiation and soil heat flux values for January 24-25, 1963.

December 13-14, 1962 (Fig. 85), was a warmer night with considerable modification in observed radiation values. The humidity was low but not as low as on the previous night. The incoming radiation was higher, and this made the net radiation value less than it was on the night before. At approximately 2:00 AM there was an abrupt change in the incoming radiation value which in turn was reflected in the net radiation reading. The outgoing radiation did not show any appreciable change after 8:00 PM on December 13. The wind averaged approximately 2 mph all night prior to the start of the wind machine.

The soil heat flux was relatively constant on December 12-13 until 2:00 AM when it dropped sharply (Fig. 84). The freezing of the heat flow plates and the surrounding soil may have occurred at this time, giving the change in value.

Radiation and soil heat flux values for 4 other nights when the wind machine was operated at least part of the night are shown in Figs. 86, 87, 88 and 89. The radiation values on all of these nights were in the same order of magnitude. The net radiation was approximately -0.160 Langleys per minute.

The soil heat flux on the 4 nights was somewhat variable. This possibly could be explained by the soil temperature or the moisture content which would be reflected in the conductivity of heat to the surface.

Net radiation values in Florida were higher than those reported from California citrus groves by Brooks (13).

Brooks' values ranged from -22 to -25 Btu per hour, or if converted to Langleys per minute, the values would be -0.099 to -0.114 Langleys per minute. On the night of December 12-13, 1962, the net radiation value averaged -0.190 Langleys per minute or -42 Btu per hour. This high value apparently is not the normal net radiation that can be expected on an average night in Florida. When net radiation was recorded on most of the other nights, readings were in the area of -0.160 Langleys per minute or -35 Btu per hour.

The maximum values which were reached on December 12-13, 1962, can be explained in part by the low incoming radiation value. The difference between -0.114 and -0.160 Langleys per minute is more difficult to explain, but it can probably be traced to soil differences between Florida and California. Soil temperatures indicate that the soil at 4 inches of depth had a minimum of 36° F and a maximum of 46° F for December 13, 1962. Soil temperature readings for January 4, 1963, show a minimum of 46° F and a maximum of 56° F. Average readings for December, 1962, were a minimum of 51.0° F and a maximum of 59.9° F. January averages were 51.9° F and 60.8° F, respectively.

The higher net radiation values in Florida may be due, in part, to the higher soil temperatures that occur in the winter months. California temperatures usually range slightly lower. The thermal conductivity of Florida soils is normally very good with the soils at or near field capacity during most freezes. Cold air masses

moving down the Florida peninsula are preceded by a cold front which carries rain showers with it. The amount of rainfall varies, but it is usually in the range of 0.25 to 0.50 inches.

The high soil temperature combined with good thermal conductivity increases the amount of outgoing radiation. When the net radiation value is calculated under these circumstances, it would be higher than one calculated for low soil temperatures with dry soil.

Wind Values: Wind values were quite variable at the same height in different locations, but there was an even greater variation when different heights were compared. Tables 5 and 6 show average wind speeds at 5 and 20 feet.

Wind speeds with leaves on the trees (Table 5) indicate that a wind speed of 2 mph or more at 20 feet is necessary to cause some convective movement at the 5-foot level. Little data was obtained at low wind speeds, but that which was available would indicate this relationship to be true. Even at wind speeds of over 6 mph at 20 feet, the 5-foot level only indicated a 2 mph movement.

Trees without foliage (Table 6) appeared to show the same relationship between 5 and 20 feet. Wind movement had to be 2 mph or more at the 20-foot level to record any air movement at 5 feet. The range of values obtained makes a good cross section for trees without leaves.

Wind profiles (Figs. 90, 91 and 92) also show the reduction of wind movement in the tree area. Values shown

Table 5

Average wind speed values at 5 and 20 feet for citrus trees with foliage, without the wind machine operating

| Date | Time | Tower # 1 | | Tower # 2 | |
|---|---|---|---|---|---|
| | | 5 feet | 20 feet | 5 feet | 20 feet |
| 12/10/62 | 8:55-9:55 PM | 0.00 | 0.00 | 0.00 | 0.00 |
| 12/12/62 | 5:35-5:50 PM | 0.90 | 3.72 | 1.34 | 4.04 |
| 12/12/62 | 5:50-6:10 PM | 0.78 | 3.16 | 1.34 | 3.36 |
| 12/12/62 | 6:30-7:00 PM | 1.02 | 4.49 | 1.68 | 4.70 |
| 12/12/62 | 8:00-9:00 PM | 1.79 | 5.20 | 1.45 | - |
| 12/13/62 | 1:40-2:35 AM | 2.02 | 5.05 | 1.34 | - |
| 12/13/62 | 3:30-4:30 AM | 1.57 | 4.70 | 1.14 | - |

Table 6

Average wind speed values at 5 and 20 feet for citrus trees without foliage, without the wind machine operating

| Date | Time | Tower # 1 | | Tower # 2 | |
|---|---|---|---|---|---|
| | | 5 feet | 20 feet | 5 feet | 20 feet |
| 1/3/63 | 11:10-11:30 PM | 0.00 | 1.57 | 0.00 | 1.34 |
| 1/4/63 | 1:10-1:35 AM | 0.00 | 1.57 | 0.00 | 1.39 |
| 1/4/63 | 2:35-2:45 AM | 0.68 | 3.60 | 0.00 | 3.36 |
| 1/8/63 | 3:00-3:15 AM | 0.00 | 1.68 | 0.00 | 2.12 |
| 1/8/63 | 4:30-5:00 AM | 0.00 | 0.50 | 0.00 | 1.23 |
| 1/21/63 | 8:16-9:13 AM | 1.02 | 4.26 | 1.12 | 3.82 |
| 1/21/63 | 10:21-10:50 PM | 0.67 | 3.14 | 0.67 | 3.03 |
| 1/22/63 | 2:00-2:17 AM | 0.00 | 0.78 | 0.00 | 1.12 |
| 1/22/63 | 4:10-4:30 AM | 0.00 | 2.80 | 0.00 | 2.36 |
| 1/24/63 | 8:54-9:09 PM | 1.46 | 4.07 | 1.57 | 4.26 |
| 1/24/63 | 9:24-10:46 PM | 0.90 | 2.70 | 0.90 | 2.36 |
| 1/25/63 | 12:54-1:14 AM | 0.00 | 1.39 | 0.00 | 1.57 |
| 1/25/63 | 6:10-6:55 AM | 1.47 | 4.93 | 1.57 | 4.15 |

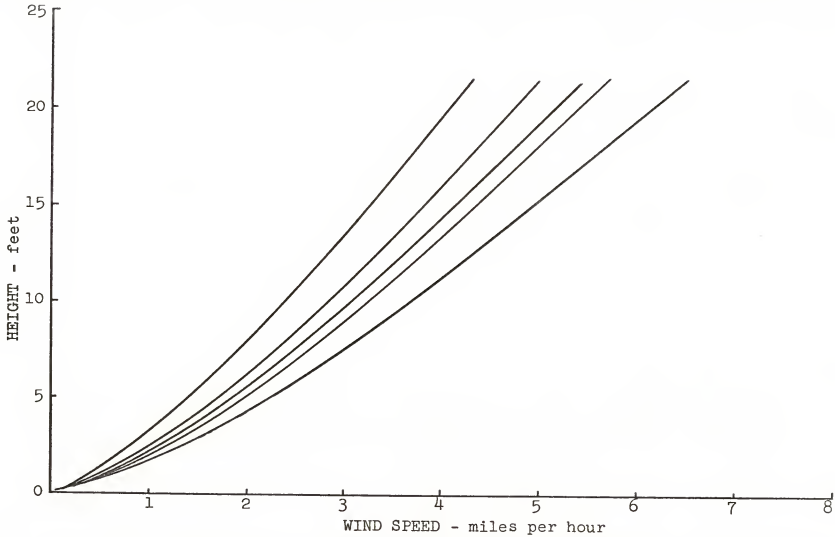



Figure 90. Comparison of the average wind speed with height in a citrus grove with foliage on the night of December 12-13, 1962.

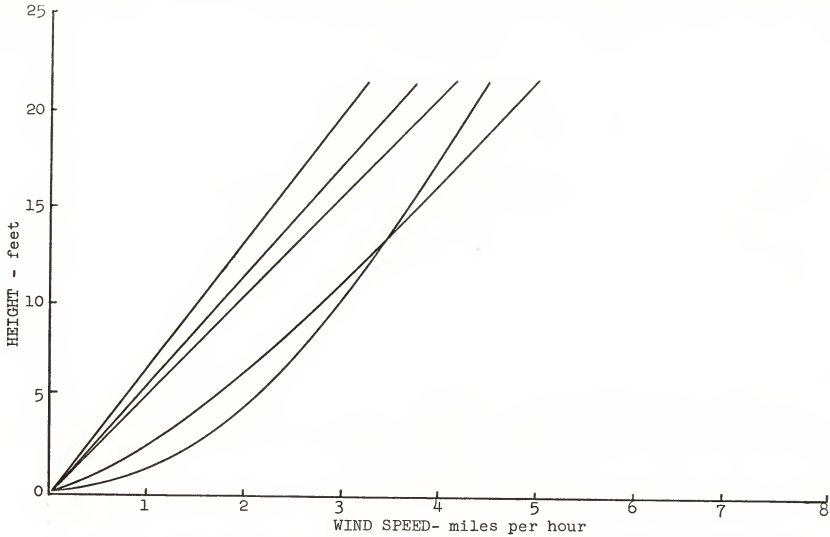



Figure 91. Comparison of the average wind speed with height in a citrus grove without foliage on the night of January 21-22, 1963.

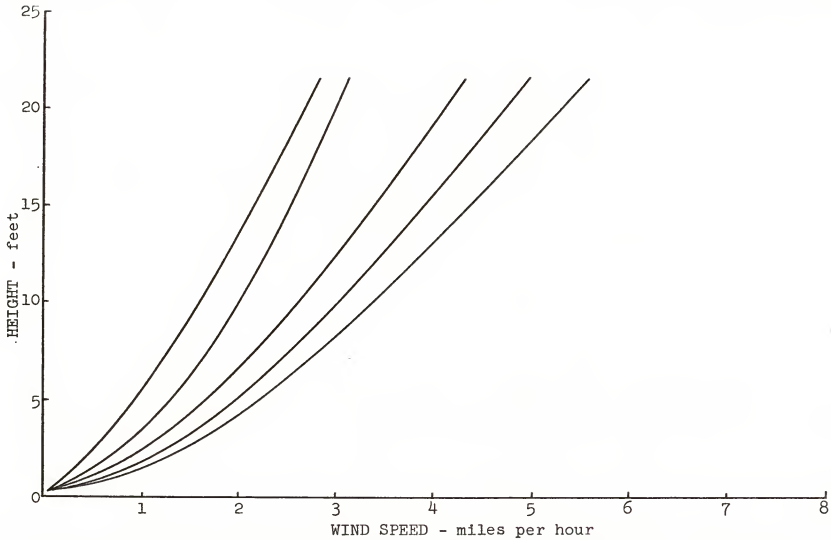



Figure 92. Comparison of the average wind speed with height in a citrus grove without foliage on the night of January 24-25, 1963.

in Fig. 90 show the profiles for December 12-13, 1963, with the leaves still present on the trees. Wind profiles taken later in the year (Figs. 91 and 92) are for defoliated trees. Comparison of values in Figs. 90 and 92 indicate there was little difference in the profiles with leaves present as compared to the absence of leaves. If differences were present, they were very small at the 5-foot level. More information is needed to improve the reliability of these data.

The surface of the grove at tree top height was apparently rough with the foliage present. Even with the foliage gone, the remaining twigs and branches were able to keep most of the wind activity above tree top level until the wind reached at least 2 mph; then eddy currents were able to reach the 5-foot level.

Inversions and Foliated Trees: The presence of foliage in the citrus grove had a definite influence on the temperature profile of an inversion. Ordinarily, over an open field, one would expect to find a single radiation surface. In the citrus grove there were 2 definite radiating surfaces; one was located at ground level and the other approximately at a level equal to a line drawn through the tree tops (Fig. 93). Inversion profiles in a foliated grove under relatively calm conditions, that is winds less than 2 mph, are shown in Figs. 94 and 95. It can be noted that the temperature change in the first 20 feet was relatively small when compared with the change from 20 to 50 feet.

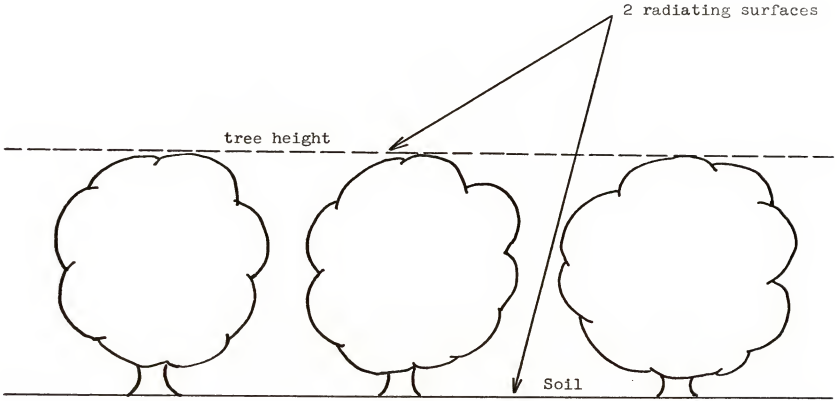



Figure 93. Diagram of a citrus grove showing the double radiating surface, one surface at the ground and the other at a level even with the tops of the trees.

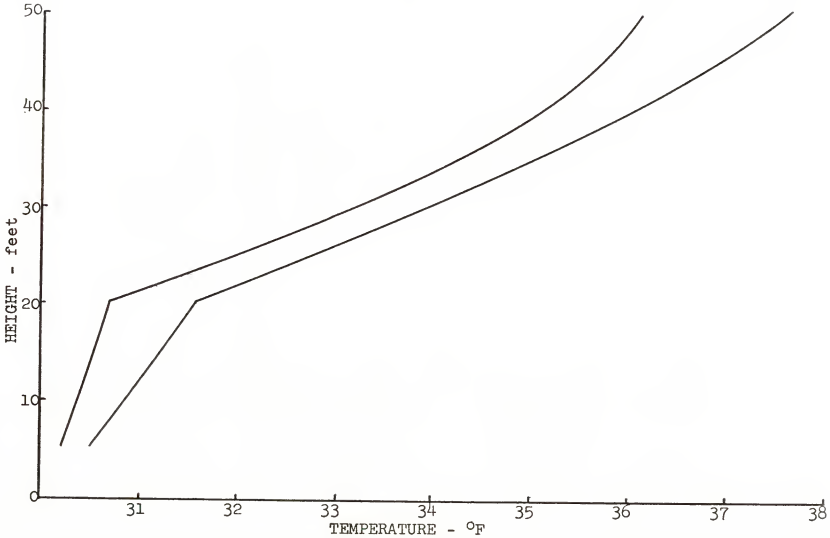



Figure 94. Inversion profiles for 2 locations from 5 to 50 feet in a citrus grove with foliage on December 10, 1962.

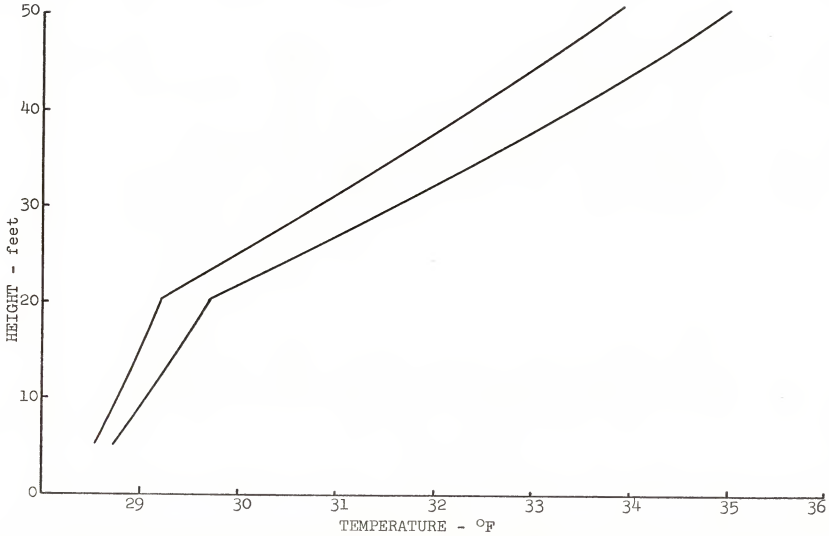



Figure 95. Inversion profiles for 2 locations from 5 to 50 feet in a citrus grove with foliage on December 11, 1962.

The rows of trees with leaves and branches that came close to the ground and with trees that joined branches with one another appeared to act as dams which trapped and held large quantities of cold air in the grove. This was especially true when the rows ran at right angles to the natural air drainage.

The cold air accumulated between the trees mainly due to the radiation processes taking place from the ground and exposed portions of the tree. The majority of the long wave radiation starts from the soil surface. Some was lost directly to space, but the rest was intercepted by parts of the tree. Eventually, this radiation was emmitted from the outer surface of the tree into space. As this radiation continued, the air in the tree zone continued to cool. Unless some means of moving this air away from the tree zone was supplied, the microclimate in the tree zone became colder. With the trees acting as dams, this air could not drain out of the grove.

The same group of trees without foliage did not show this typical dual radiation surface. Profiles from trees without leaves are shown in Fig. 96. Profiles of January 3-4, 1963, indicate that the second radiation surface did appear on trees without foliage in an absolute dead calm (Fig. 97). The second surface at tree top height did not appear if the wind was blowing over 1 mph.

Without foliage, apparently enough natural drainage occurred with light air movements to alleviate the damming

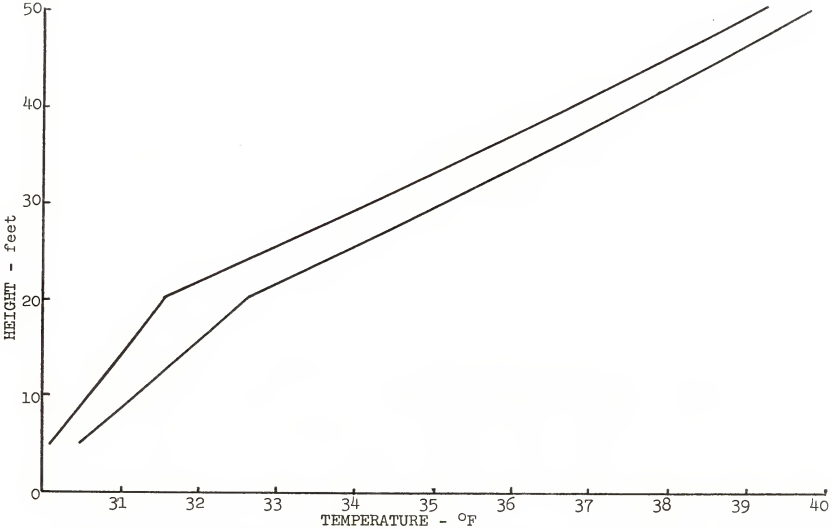



Figure 96. Inversion profiles for 2 locations from 5 to 50 feet in a citrus grove without foliage on January 3, 1963.

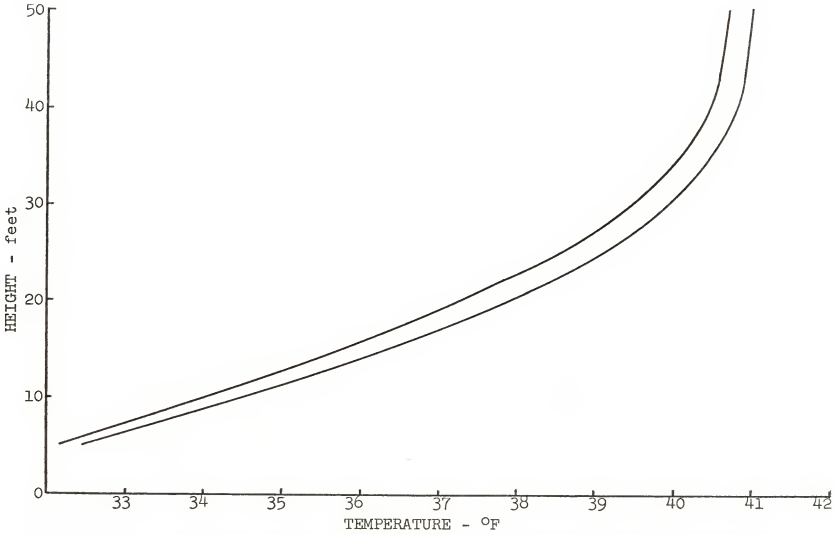



Figure 97. Inversion profiles for 2 locations from 5 to 50 feet in a citrus grove without foliage on January 4, 1963.

effect. Without foliage, a larger percentage of the radiation went directly to space rather than passing through the intermediate steps of reradiation within the tree. This caused most of the radiative cooling to occur near the ground surface. As this cool air drained out of the grove at the lower elevations, other air moved in to take its place. This gave a stronger inversion strength near the ground rather than the stacking up of cold air between the rows of trees.

Inversions and Wind: The inversion strength in the zone from 5 to 50 feet is quite variable depending on the meteorological conditions existing at the time of measurement. Geiger (39) stated that strong inversions exist when conditions are stable, but when air movement reaches 6 meters per second, further increases in wind velocity have no added effect on the temperature differences.

Fig. 98 shows some typical examples of inversions at the Brown grove as they occurred with various wind speeds. There was a relationship between the strength of the inversion and the rate of convective flow over and through the citrus trees. As the air movement increased, the inversion strength decreased rapidly. Under ideal inversion conditions, calm with no wind or drift, a strong inversion of 11.6° F existed. When the wind movement reached 2 mph, the inversion strength dwindled to approximately 6.2° F. With wind speeds of 5 mph or greater, the inversion strength was usually 2.0° F or less.

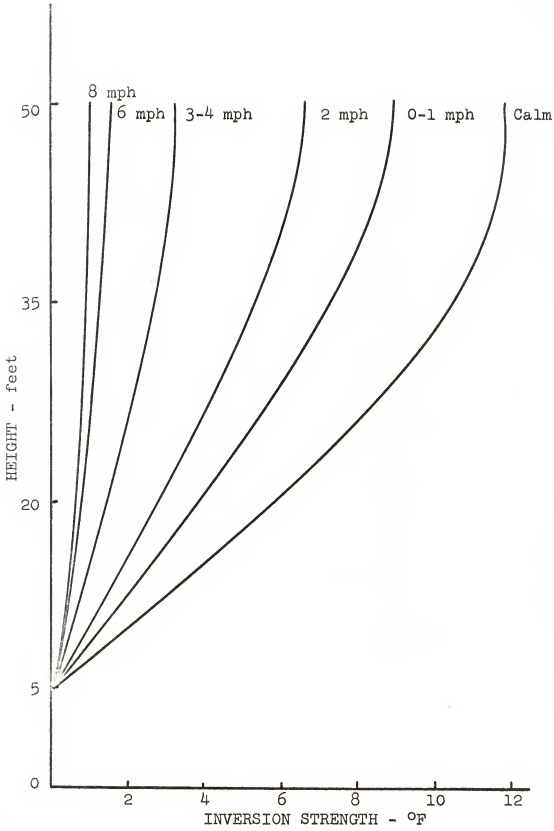



Figure 98. The relationship of wind speed to inversion strength at heights from 5 to 50 feet.

Comparing this information to that published by Geiger (39), we find a good correlation. The 6 meters per second can be converted to 13.4 mph. It was at this point that Geiger stated the inversion would no longer exist. During the nocturnal period of December 12-13, 1962, comparable conditions existed in the Brown grove. Winds of this night gusted above 10 mph and averaged above 6 mph. From midnight on, no inversion could be measured, and it was actually warmer at 5 feet than at higher elevations. Some temperture profiles are shown in Fig. 99. At 4:00 AM, the profile reached its greatest negative value, 1.2$^{\circ}$ F colder at 50 feet than at 5 feet.

It is apparent, under this set of conditions, that the trees were containing some of the heat being released in the grove area and probably were reducing the wind effect at the lower levels. The wind was moving from the northwest to the southeast or in a diagonal direction to the rows which ran in an east-west direction. Had the wind been moving directly down the middle between the rows, this effect might have been eliminated or at least greatly reduced.

A study of the changes in the inversion profile between 5 and 50 feet was made on the night of January 3-4, 1963, at a point 300 feet southeast of the wind machine tower. Figs. 100, 101 and 102 show the continuous profile during a period of approximately 4-1/2 hours with and without the wind machine in operation. In each of the 3 figures, there

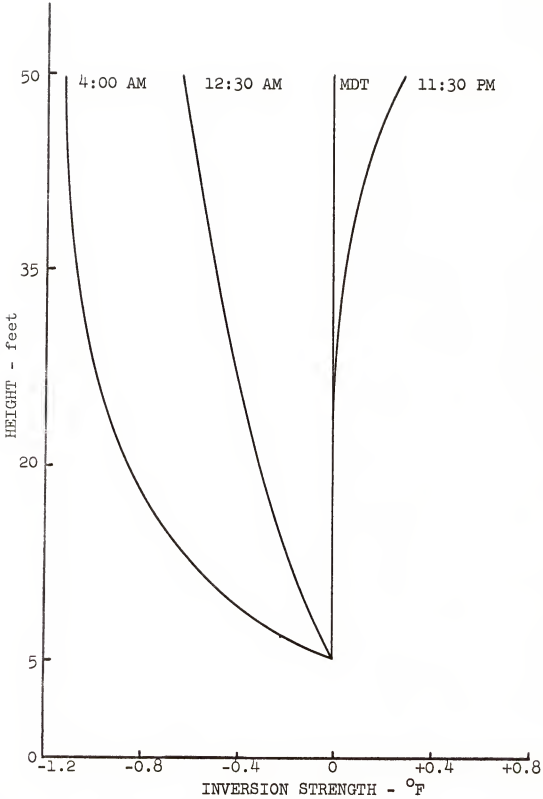



Figure 99. Temperature profiles at heights from 5 to 50 feet on December 12-13, 1962, showing the negative inversion in high wind.

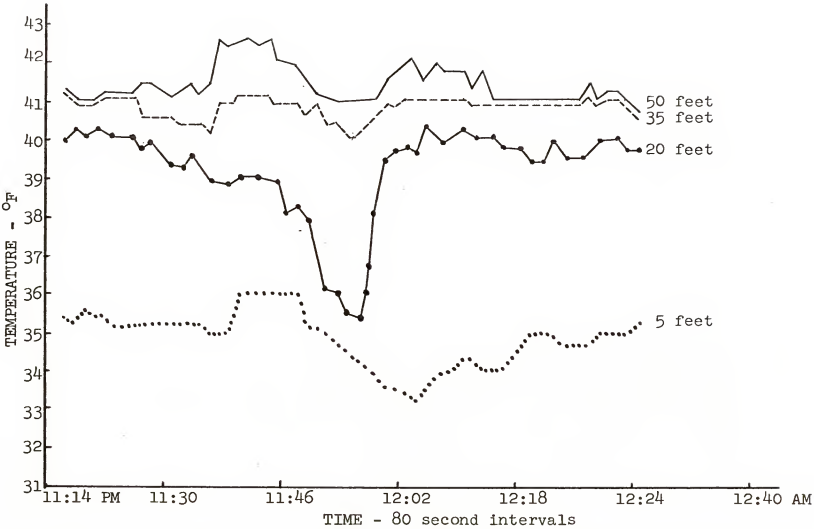



Figure 100. Changes in the inversion profile between 5 and 50 feet as related to the natural convection on January 3-4, 1963, without the wind machine in operation.

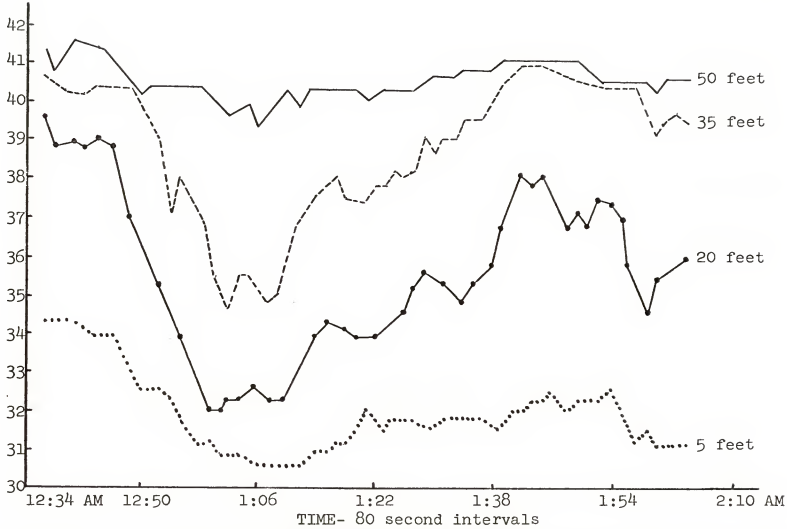



Figure 101. Changes in the inversion profile between 5 and 50 feet as related to the natural convection on January 4, 1963, without the wind machine in operation.

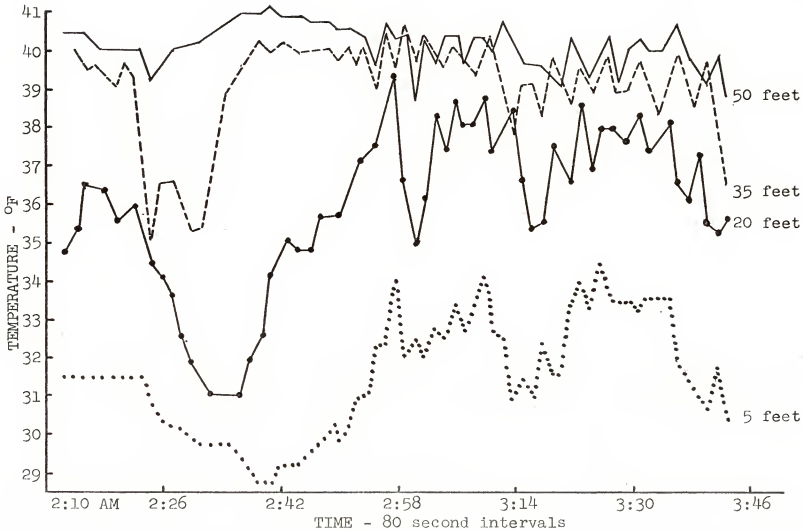



Figure 102. Changes in the inversion profile between 5 and 50 feet as related to the natural convection on January 4, 1963, with and without the wind machine in operation. The machine was started at 2:45 AM.

is at least 1 period when the convection was nil at and below tree top level.

Fig. 100 shows the period from 11:15 PM to 12:30 AM. The wind speed at 11:15 PM was 1.3 mph at the 20-foot level whereas the 5-foot level had less than 0.5 mph. At 11:15 PM the wind stopped and the air was calm below 20 feet. Changes in the inversion profile began to take place quite rapidly with the 20-and 35-foot levels reacting most rapidly. The 50-foot level never actually decreased in temperature but instead showed a slight increase. There apparently was still some convective movement in the layers above 50 feet that kept the temperature rising. The calm appears to have begun in the 35 to 50-foot area and then moved down the profile toward the surface. This is reflected in the temperature decrease at the various levels. The decrease in temperature ceased at the 35-foot level at 11:35 PM, at the 20-foot level at 11:55 PM and at the 5-foot level at about 12:05 AM. The largest temperature loss was at the 20-foot level where a $5^{\circ}$ F loss was noted. After the winds had increased to 1.2 mph, the temperatures at all 4 levels had regained the same approximate temperature as they held before the calm.

Following a period of light convection, a second period of calm occurred which was of longer duration than the first calm (Fig. 101). Again the changes in the profile pattern appeared to begin at the upper levels and then progress to the lower levels. This pattern was probably due to the

continued action of turbulence and eddy currents moving downward after the wind had ceased at the 50-foot level. The 20-and 35-foot levels showed the greatest change in temperature during this calm period, losing 6.3° F and 7.8° F respectively, over a 35-minute period. The 5-foot level gave up 3.6° F whereas the 50-foot level lost only 2.3° F.

The warming trend following the calm was accompanied by winds averaging 1.4 mph. This warming began with the upper layers and worked its way down the profile similar to the cooling cycle. The largest influence was noted at the 20-and 35-foot levels where the decreases had been the greatest. The 5-and 20-foot levels did not regain all the temperature losses as in the period following the preceding calm whereas the 35-and 50-foot levels came back approximately to the same levels as previously recorded.

At approximately 2:10 AM, a third calm period started (Fig. 102). Here again there was a rapid temperature drop, especially at the 5, 20-and 35-foot levels. Temperatures reached the critical point for wind machine initiation, 30° F at the 5-foot level at 2:25 AM. The wind machine was placed in operation at 2:25 AM, and the influence was almost immediately felt at the inversion tower even though it was 300 feet from the wind machine in the down drift position. The temperatures at the 35-and 50-foot levels were depressed slightly and began to fluctuate as the wind machine cycled. The temperatures at the 5-and 20-foot

levels showed an immediate increase in temperature and also reflected the cycling of the wind machine.

Even with the wind machine in operation, the influence of the natural convective forces could be noted. At approximately 3:00 AM and again at 3:30 AM, depressions appeared in the profiles which were apparently due to calm periods in the wind activity.

## SUMMARY AND CONCLUSIONS

This research was divided into 4 phases. The first was to design a satisfactory temperature measuring system that would record temperatures over approximately 10 acres in a short period of time. With the system in operation, the second phase, the determination of the basic nocturnal microclimate of a citrus grove was then studied. The extent to which wind machines provide protection to citrus groves from cold temperatures was the next phase. The final phase was to formulate a means of estimating the area of protection that the machine could be expected to give under various conditions.

The original thermistor network tested during the 1961-62 season was found to be unsatisfactory, but some information and experience was gained even though the overall picture could not be measured. By the fall of 1962, a reliable thermistor network had been built and tested. Radiation and soil heat flux instrumentation had been installed and worked satisfactorily. Some of the results obtained were as follows:

(1) The data and information obtained from the wind machine trials were in general agreement with the results previously published in California, Australia and other areas. The wind machine

was able, with an inversion and relatively stable conditions, to open a pocket in the atmosphere near the ground by pushing back or entraining the cold air into its jet. Once the machine had pushed out the cold air from the immediate area around its base, it held this cold air back by continually adding more heat and convective forces each time a cycle was made.

(2) The shape of the area of protection was found to be kidney-shaped in many instances instead of being round or oval as previous research had indicated. The kidney-shaped isotherm pattern pivoted around the wind machine base as the fan rotated.

(3) The temperature at any given point in the system was not constant but was continually falling or rising, depending on the position of the point relative to the turning jet. The maximum rise in temperature was recorded between 90 to 150 degrees after the jet had passed the point. The period of the coldest temperature was just before the passage of the jet over the point.

(4) All air movement was not away from the wind machine as might be indicated by previous published works. The cool air moved in toward the wind machine base just in advance of the turning jet and was apparently the reason for

the indentation in the isotherms, giving the kidney-shaped pattern.

(5) The majority of the turbulent mixing did not occur as the fan blew directly toward a point, but a large percentage of the mixing occurred 90 degrees or more after the machine was pointed at an area. Some eddy current action could be observed in advance of the jet as well as behind it. By far, the largest eddy current action followed the passage of the turning jet.

(6) The wind machine had only a very slight influence on the radiation values, and this was only as the jet passed directly over the recording plates. The soil heat flow plates were not affected by the wind machine with the values recorded remaining constant.

(7) Radiation losses on clear, calm, cold nights in Florida citrus groves were as high as 42 Btu per hour per square foot. Average readings were 30 to 35 Btu per hour per square foot. These values were considerably higher than the 20 to 25 Btu per hour per square foot reported by Brooks (13) from California citrus groves. The higher values were probably due to higher soil temperatures and better soil conductivity.

(8) The wind machine can modify the rate of temperature fall near the ground by moving the warmer

air from upper elevations and mixing it with the cooler air near the radiating surfaces. In order to accomplish this, an inversion must be present, and the air temperature must be above the freezing point of citrus. Temperature losses of 2.0° F per hour were reduced to approximately 1.0° F per hour.

(9) The area of protection was related to the inversion strength and also the natural convective forces. This area was not isothermal, and as the distance away from the wind machine increased, the degree of temperature modification decreased. With an inversion of 8.0° to 9.0° F in the first 50 feet above the surface, approximately 10 acres was modified 1.0° F; 5.70 acres 2.0° F; 2.35 acres 3.0° F and 1.25 acres 4.0° F.

(10) The wind speed at 20 feet must reach an average of 2 mph before any wind movement can be recorded at the 5-foot level. This is true on citrus trees with or without foliage.

(11) The response time at the 5-foot level after the wind machine was started took as long as 35 minutes before well-defined isotherms were developed. At the 20-foot level, the response time was usually less than 15 minutes and at times only 10 minutes. Defoliated trees had a faster response time at the 5-foot level,

showing well-defined isotherms in 25 minutes or less.

(12) The citrus grove showed a double radiation surface. The primary surface was at the ground level, and the secondary surface could be found at the approximate level of a line drawn through the tree tops horizontal to the ground.

(13) Wind speed studies indicated that no added value was given by the wind machine when the average wind speed reached 4 to 5 mph. Apparently there was sufficient mixing by the natural convection to reduce the inversion strength to nearly 0.

(14) The wind movement created by the wind machine was recorded at distances of 100, 200 and 300 feet from the wind machine. As the jet moved farther away from the machine, the amount of air movement became less and less. On occasions, the 300-foot station did not record the passage of the jet.

(15) The wind machine was able to modify the vertical profile after it was put into operation. The temperatures at 50 and 35 feet were reduced whereas those at 5 and 20 feet showed an increase. The amount of change recorded was related to the inversion strength and natural convection.

(16) Very little or no protection could be observed when the inversion strength was less than $1.0^{\circ}$ F. When the inversion strength became greater than $3.0^{\circ}$ F, the area of protection increased quite rapidly. The area of protection at the $1.0^{\circ}$ F level was 10 acres or more when the inversion reached $8.0^{\circ}$ F.

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## BIOGRAPHICAL SKETCH

Robert Lewis Reese was born in Newark, New Jersey, on November 23, 1926. He received his elementary and secondary education through the eleventh grade at Maplewood, New Jersey, finishing his final year of high school at Vero Beach, Florida. Upon graduation from Vero Beach High School in 1945, he was inducted into the military service where he served 13 months in the 88th Division of the United States Fifth Army in Italy.

On his return to Florida in 1947, he enrolled as a student in the College of Agriculture of the University of Florida. In June, 1950, he graduated with the degree of Bachelor of Science in Agriculture, with honors.

Immediately after graduating, he was employed by the Florida Agricultural Experiment Station, Indian River Field Laboratory, Fort Pierce, Florida. He served 9 years at this station.

In September, 1959, he entered the University of Florida Graduate School. In August, 1961, he received the degree of Master of Science in Agriculture.

In 1959, he was appointed graduate assistant in the Department of Fruit Crops. In 1960, he was transferred to a research assistantship with the Florida Agricultural Experiment Station in Gainesville, Florida. He assumed his

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This dissertation was prepared under the direction of the chairman of the canidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Agriculture and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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